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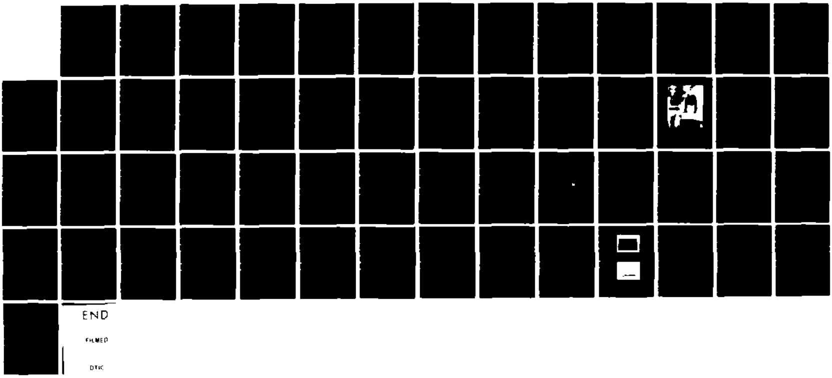

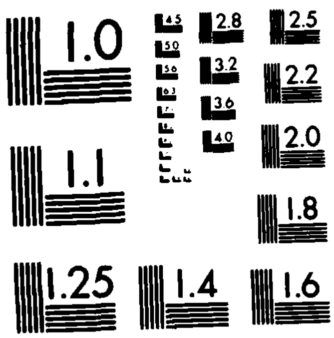

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Adhesive Bond and Composite Strength Screening System Developmental Study

S. Y. Chuang
F. H. Chang
J. R. Bell

Prepared by
General Dynamics
Fort Worth Division
P.O. Box 748
Fort Worth, Texas 76101

June 1984

Final Report

US Department of Transportation
Federal Aviation Administration
Technical Center
Atlantic City Airport, N.J. 08405

84 09 11 056

NOTICE

Technical Report Documentation Page

1. Report No. DOT/FAA/CT-84/5	2. Government Accession No. AD-A145 460	3. Recipient's Catalog No.
4. Title and Subtitle ADHESIVE BOND AND COMPOSITE STRENGTH SCREENING SYSTEM DEVELOPMENTAL STUDY		5. Report Date June 1984
		6. Performing Organization Code
7. Author(s) S.Y. Chuang, F.H. Chang, and J.R. Bell		8. Performing Organization Report No. FZM-7184
9. Performing Organization Name and Address General Dynamics Corporation/Ft. Worth Division P.O. Box 748 Ft. Worth, Texas 76101		10. Work Unit No. (TRAIS)
		11. Contract or Grant No. DTFA03-81-C-00076
12. Sponsoring Agency Name and Address U.S. Department of Transportation Federal Aviation Administration Technical Center Atlantic City Airport, New Jersey 08405		13. Type of Report and Period Covered FINAL November 1981 to March 1983
		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

This report summarizes the results from an eighteen-month developmental study of an adhesive bond and composite strength screening system. A system based on the utilization of a high power ultrasonic (HPU) technique was developed. Several bonded structures: metal-to-metal, composite-to-composite, composite-to-metal, and composite-to-honeycomb core structures, were fabricated with various bonding conditions for system evaluation. The HPU power levels required to disrupt weak bonds without damaging good bonds in these structures were established. The ability of the system to screen weak bonds in some selected structures was successfully demonstrated. Analytical studies of HPU effects on bonded structures were also conducted. Further improvements and developments of the system are recommended and discussed.

17. Key Words Nondestructive Testing, Adhesive Bond, Aircraft Materials	18. Distribution Statement This document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified		

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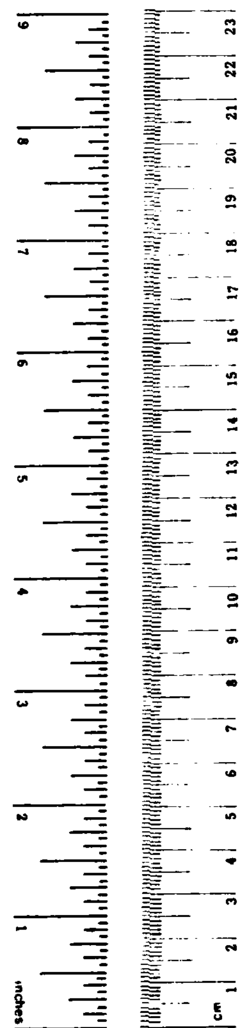
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

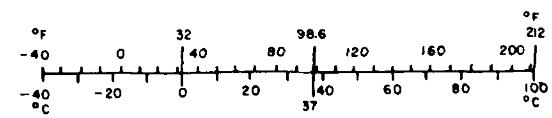
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



FOREWORD

This final technical report was prepared by General Dynamics, Fort Worth Division, under Contract No. DTFA03-81-C-00076 with the Federal Aviation Administration (FAA) Technical Center, where L. M. Neri acted as Technical Monitor. Under the contract, a portable adhesive bond strength screening system based on the high power ultrasound technique was developed and tested.

This program was performed in the NDE group of the Materials and Processes Section of the Structures and Design Department of Fort Worth Division, General Dynamics Corporation, Fort Worth, Texas. Dr. F. H. Chang was the program manager with Dr. S. Y. Chuang as the principal investigator for technical development. Key contributors to the program include J. R. Bell and J. S. Green on specimen testing, B. O. McCauley on specimen fabrication, J. D. Anderson on finite element stress analysis, and J. R. Eisenmann and Dr. D. J. Wilkins on structural analysis. Valuable suggestions and technical directions from J. R. Soderquist in FAA are gratefully acknowledged.

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EXECUTIVE SUMMARY

During the past decade, composite components have been used increasingly in primary aircraft components because of their high specific strength and stiffness properties. The increasing usage of adhesively-bonded and composite structures in transport aircraft has necessitated the need for better quality control and nondestructive inspection (NDI) of these structures. Quality control of adhesive joints and advanced composites includes chemical characterization of adhesive materials and composite prepregs, as well as process control to assure that the surfaces to be bonded are properly cleaned. Efforts in the process control area have been fairly successful in recent years with limited production rate and areas of application. Chemical characterization for raw materials, however, has not been able to provide the assurance that material systems with the same chemically and physically identifiable characteristics can be processed into components with repeatable strength and quality under presently specified processes. The problem in adhesive joint and composite laminate quality is most acute when the manufacturing of the parts has reached a full production stage and requirements for material supplies, facilities, and human resources have reached their peaks.

NDI of adhesive joints and advanced composite structures has been successful in detecting disbonds, voids, delaminations, and foreign inclusions of a size that would affect service life of the components. However, the type of bond defect that does not produce a void but has weak bond strength, a condition created by improperly cleaned surfaces or a defective adhesive system, cannot be detected by state-of-the-art NDI methods. For production inspection of aircraft structures, the inability of current NDI procedures to detect weak bonds is remedied by subjecting the structure to a proof loading test as an acceptance inspection (Ref. 1). The proof tests are expensive and require extensive facilities. A more cost-effective way is needed to guarantee the joint integrity of adhesive bonds and composite laminate quality. In another issue, the aircraft may suffer service damages or environmental degradations not anticipated in the damage envelope prescribed in the proof loading acceptance test. The need for an NDI method to screen the bond strength in adhesive joints and composite laminates is especially urgent in field and depot inspection.

At General Dynamics Fort Worth Division, the problem of weak bond detection and composite structure inspection has been investigated through Independent Research and Development (IRAD), AFWAL/ML contracts, and DARPA/AFML funding for the past 10 years. After exhaustive studies on the more conventional NDI techniques (such as ultrasonics), in an attempt to characterize the weak bond, it has been concluded that conventional NDI techniques cannot detect weak bonds (Ref. 2-5). In 1979 a study was conducted on utilizing the stress waves generated by a high power ultransonic unit to impinge on the adhesive bondline. The stress waves are of sufficient amplitude to disrupt marginal bonds so that they can be detected by conventional ultrasonic techniques. Bonds with acceptable strength will not be affected by the stress waves. Preliminary evaluation of this novel bond strength screening technique proved it to be highly promising.

In 1981 an 18-month program was awarded to General Dynamics Fort Worth Division by FAA (Contract No. DTFA03-81-C-00076) to develop an adhesive bond strength and composite structure screening system to be used for field/depot NDE inspection of commercial aircraft. This report describes the work accomplished under this contract. A portable high power ultrasound (HPU) bond strength screening system was constructed. Several types of adhesively bonded structures: metal-to-metal, composite-to-composite, composite-to-metal, and composite-to-honeycomb core structures, were fabricated and evaluated by the system. The power level of the high power ultrasound required to disrupt weak bonds without damaging good bonds was determined for each type of bonded structure. Analytical studies of effects of the high power ultrasound on bonded structures were also conducted in this program. For the system to have a wide range of applications, however, further developments are recommended.

INTRODUCTION

PROGRAM OBJECTIVE.

The objective of this program was to develop a quantitative, cost effective, and portable nondestructive inspection (NDI) system to screen bond strength in adhesively bonded and composite aircraft structures. The system can be applied to metal-to-metal, composite-to-metal, and composite-to-honeycomb core structures. The system may be used at both manufacturing and depot levels to screen adhesive bond strength of production parts and repaired components.

BACKGROUND.

Research work on nondestructive testing techniques for adhesively bonded and composite structures has been conducted for many years. The most commonly used inspection method is the conventional ultrasonic C-scan technique operating in a pulse-echo or through-transmission mode. Ultrasonic techniques are most effective in detecting disbonds, voids, delaminations, and foreign inclusions. However, they are ineffective for the detection of weak bonds at the adhesive joints. The weak bonds are mostly caused by not properly cleaning the surfaces of the substrates to be bonded. There is no air space at the adhesive joints because the substrate and the adhesive are in intimate contact with each other. There is not, however, strong adhesion at the joint. This results in no interface for ultrasound reflection and renders the conventional ultrasonic inspection techniques inadequate for detecting these weak bonds.

Ultrasonic spectroscopy has been used in an attempt to characterize the interfacial bondline characteristics of the weak bond (Ref. 3 and 4). However, it was concluded that the technique cannot discriminate weak bonds because there are too many variables in the adhesive bondline affecting the ultrasonic parameters. Another category of NDI techniques based on the ultrasonic resonance principle has also been used in an attempt to measure bond strength. In the resonance technique, a relatively low frequency ultrasound (approximately 100 KHz) is propagated into the adhesively bonded structure. The structure serves as a source of acoustical damping to the incident ultrasound. The degree of damping is reflected by the resonance responses of the incident waves. The acoustical damping effect from the structure is a gross phenomenon. A weak bond, with intimate contact at the bondline interface, does not appreciably affect the mechanical damping of the incident acoustic waves. Therefore, the resonance-type testers, including Fokker bondtester, are incapable of measuring the adhesive bond strength of the structure. Nevertheless, these techniques may be able to measure the cohesive bond strength.

TECHNICAL APPROACH.

The technical approach used in this program was based on the utilization of a high power ultrasonic technique. The high-power ultrasound was generated by a piezoelectric transducer and amplified by using a mechanical coupler and an exponential horn (Ref. 6). Adhesively bonded specimens were initially inspected by ultrasonic C-scan, and then were irradiated with different levels of high-power ultrasound (HPU). After the HPU irradiation, the specimens were reinspected by an ultrasonic pulse-echo technique, using an In-Service Inspection System (ISIS) developed by General Dynamics (Ref. 7), to reveal disrupted weak bonds. The essential part of this approach was to establish the HPU power level required to disrupt weak bonds without damaging good bonds in each type of selected candidate structure.

The program was divided into four (4) phases. In Phase I candidate structures representative of adhesively bonded and composite structures in commercial aircraft were selected. These candidate structures were used in the preliminary design consideration of the system and in system evaluation after fabrication. The preliminary design and layout of the bond strength screening system were done in Phase 2. System fabrication and assembly, and system demonstration were conducted in Phase 3 and Phase 4, respectively.

SPECIMEN FABRICATION

TYPES AND CONFIGURATIONS OF SPECIMENS.

Three types of specimens were chosen for this program. Figure 1 shows the specimen configurations for these three types. Type I is metal-to-metal bonded specimens designed for developmental tests. They were made from 0.125 inch thick 2024-T3 aluminum sheets bonded by high temperature curing adhesives, EA9649R or AF147. Type II is composite-to-metal and composite-to-composite specimens bonded by EA9649R adhesive. Both 10-ply and 20-ply graphite/epoxy (GrE) composites were used to fabricate Type II specimens. Type III is honeycomb core reinforced beam specimens with GrE composite skins and/or aluminum skins. Nomex™ and aluminum honeycomb cores were used for these specimens.

Each type of specimen consists of two groups, one with strong bonds and the other with weak bonds. Specimens with strong bond conditions were fabricated by using normal bonding procedures; e.g., proper surface preparations and proper cure cycles. Specimens with weak bond conditions were prepared by using improper surface treatments or improper cure processes. Detailed treatments of each specimen are listed in the first column of Tables 1 to 8. In each table, the specimen treatment, the results of bond strength tests, and the results of high-power ultrasound (HPU) tests for one type of specimen are listed.

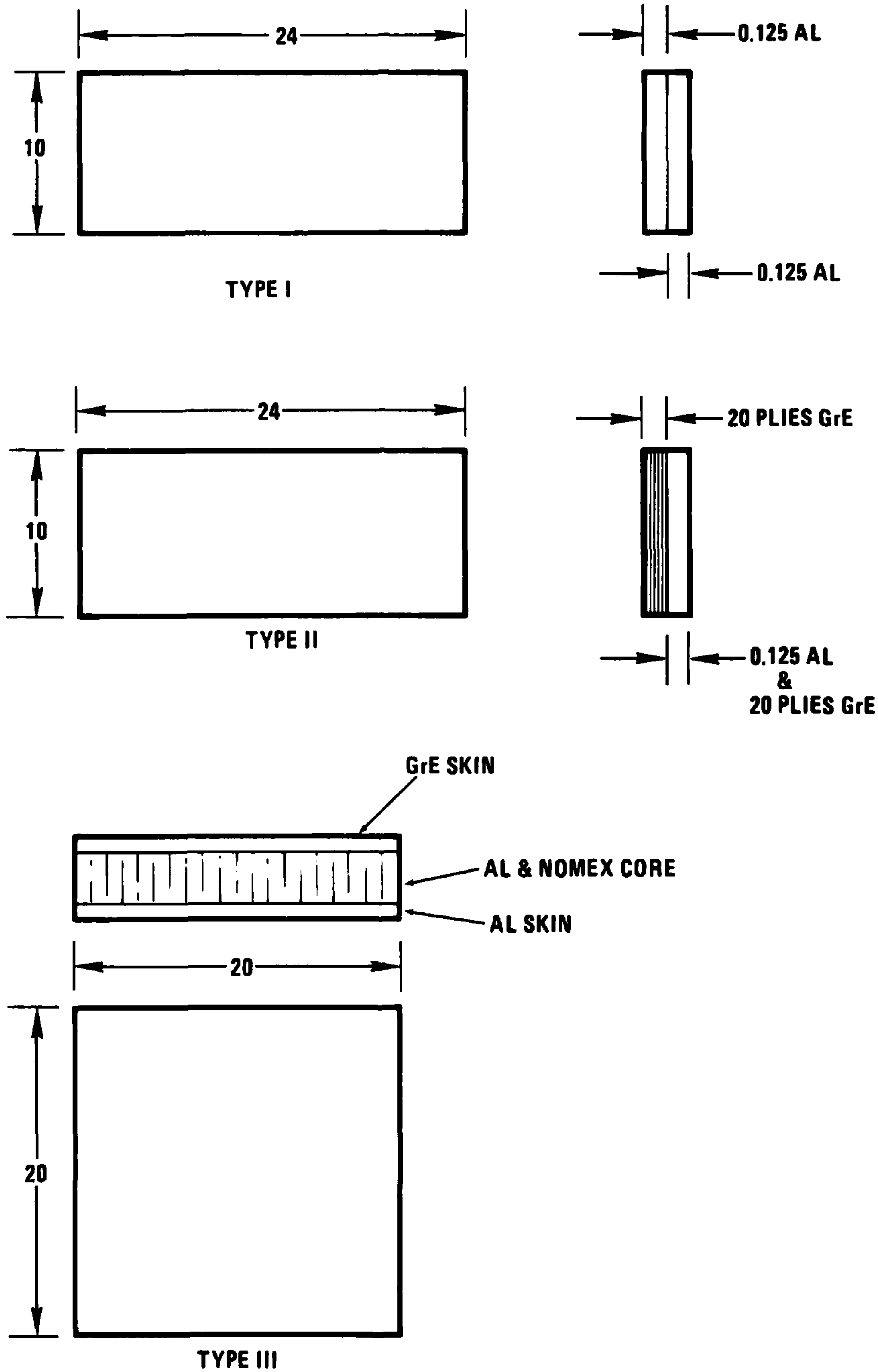


FIGURE 1 SPECIMEN CONFIGURATION

TABLE 1 TEST RESULTS OF TYPE I (Al/Al) SPECIMENS BONDED WITH EA9649R ADHESIVE

Specimen Treatment	Compressive-Shear Test		HPU Test	
	Load to Failure (KSI)	No. of Specimens Tested	Avg. Irrad. Time to Induce Debond	No. of Specimens Tested
Etched; Surface cleaned	12.3 ± 0.8	162	>10 S (No debond after 10 S of irrad.)	9(1x10x0.25 in.) 1(4x10x0.25 in.)
Unetched; Surface cleaned	10.3 ± 2.3	144	4.8 S	12(1x10x0.25 in.)
Unetched; Surface coated with WD-40 Oil	4.9 ± 0.5	342	1.3 S	12(1x10x0.25 in.) 4(4x10x0.25 in.)
Unetched; Surface coated with Frekote releasing agent	Very Weak (< 2)	Failed during machine cutting	0.3 S	5(1x10x0.25 in.)

TABLE 2 TEST RESULTS OF TYPE I (Al/Al) SPECIMENS BONDED WITH AF147 ADHESIVE

Specimen Treatment '	Compressive-Shear Test		HPU Test	
	Load to Failure (KSI)	No. of Specimens Tested	Avg. Irrad. Time to Induce Debond	No. of Specimens Tested
Etched; Surface cleaned	9.4 ± 0.1	54	>10 S (No debond after 10 S irrad.)	6 (1x10x0.25 in.)
Unetched; Surface cleaned	8.6 ± 0.3	144	>7 S (No debond after 7 S irrad.)	6 (1x10x0.25 in.)
Unetched; Surface coated with WD-40 Oil	Very Weak	Failed during machine cutting	0.5 S 1.3 S	2 (1x10x0.25 in.) 4 (4x10x0.25 in.)
Unetched; 1 coat of Frekote releasing agent	4.8 ± 0.2	16	2.6 S	1 (4x10x0.25 in.)
Unetched; 2 coats of Frekote releasing agent	Very Weak	Failed during machine cutting	1.3 S	1 (4x10x0.25 in.)
Unetched; 3 coats of Frekote releasing agent	Very weak	Failed during machine cutting	0.6 S	1 (4x10x0.25 in.)

TABLE 3 TEST RESULTS OF TYPE I (Al/Al) SPECIMENS BONDED WITH FM300K ADHESIVE

Specimen Treatment	Compressive-Shear Test		HPU Test	
	Load to Failure (KSI)	No. of Specimens Tested	Avg. Irrad. Time to Induce Debond	No. of Specimens Tested
Etched; Surface cleaned	11.2 ± 1.0	126	>5 S (No debond after 5 S of irrad.)	10 (1x10x0.25 in.)
Unetched; surface cleaned	7.1 ± 0.8	108	2.6 S	10 (1x10x0.25 in.)

TABLE 4 TEST RESULTS OF TYPE II (Comp/Comp) SPECIMENS BONDED WITH EA9649R ADHESIVE

Specimen Description & Treatment	Flatwise Tensile Test	HPU Test	
		Avg. Irrad. Time to Induce Debond	No. of Specimens Tested
Thick GrE laminate (1/8 in.); 350°F cure; Strong bond condition	Failed in laminate	>10 S (No damage after 10 S of irrad.)	2 panels (5x13x1/4 in.)
Thick GrE laminate (1/8 in.); 150°F cure; Weak bond condition	Failed in laminate	2 S (Debond under the horned area	3 panels (5x13x1/4 in.)
Thin GrE laminate (1/16 in.); 350°F cure; Strong bond condition	Failed in laminate	>10 S (No damage after 10 S of irrad.)	2 panels (5x13x1/8 in.)
Thin GrE laminate (1/16 in.); 150°F cure; Weak bond condition	Failed in laminate	1 S (Debond under the horned area)	3 panels (5x13x1/8 in.)

TABLE 5 TEST RESULTS OF TYPE II (GrE/Al) SPECIMENS BONDED WITH EA9649R ADHESIVE

Specimen Treatment	Bond Strength Test	HPU Test	
		Avg. Irrad. Time to Induce Debond	No. of Specimens Tested
Etched; cleaned	Due to warped geometry of the specimen, no shear test was performed	>4 S (No damage after 4 S of irrad. from comp. side or from metallic side)	4 (1x10x0.25 in.) 1 (10x10x0.25 in.)
Unetched; cleaned	Due to warped geometry of the specimen, no shear test was performed	2 S (Irradiate from the metallic side) >4 S (No damage after 4 S of irrad. from the composite side)	7 (1x10x0.25 in.)

TABLE 6 TEST RESULTS OF TYPE III (GrE/Al Honeycomb/Al) SPECIMENS BONDED WITH EA9649R ADHESIVE

Specimen Treatment	Flatwise Tensile Test		HPU Test	
	Load to Failure (PSI)	No. of Test	Avg. Irrad. Time To Induce Debond	No. of Test
Etched, cleaned (Bad Adhesive)	439 ± 85	3	1 S	Test 3 spots in one specimen (4x10 in.)
Etched; cleaned	745 ± 163	5	5.2 S (Damage in core)	Test 6 spots in 2 specimens (4x10 in.)
Core sprayed with WD-40 Oil	502 ± 95	7	1 S	Test 6 spots in 2 specimens (4x10 in.)
Etched; cleaned; soaked in water for 15 days	305 ± 3 (Sandwich beam test)	2	4 S (Damage in core)	2 (1x10x1 in.)
Etched; cleaned; exposed in 95% R.H. at 150°F for 15 days	292 ± 25 (Sandwich beam test)	2	4 S (Damage in	2 (1x10x1 in.)

TABLE 7 TEST RESULTS OF TYPE III (Al/Nomex Honeycomb/Al) SPECIMENS BONDED WITH AF147 ADHESIVE

Specimen Treatment	Flatwise Tensile Test		HPU Test	
	Load to Failure (PSI)	No. of Test	Avg. Irrad. Time To Induce Debond	No. of Test
Etched; cleaned; Bad adhesive	905 ± 102	3	1.3 S	Test 8 spots in 1 specimen (4x10 in.)
Etched; cleaned	1106 ± 85	3	2.6 S	Test 2 spots in 1 specimen (4x10 in.)

TABLE 8 TEST RESULTS OF TYPE III (GrE/Nomex Honeycomb/Al) SPECIMENS BONDED WITH EA9649R ADHESIVE

Specimen Treatment	Flatwise Tensile Test		HPU Test	
	Load to Failure (PSI)	No. of Test	Avg. Irrad. Time To Induce Debond	No. of Test
Sprayed 3 coats of Frekote releasing agent on each side of adhesive	89 ± 19	8	3.0 S (Debond under the horned area)	4 Specimens (5x13 in.); 3 spots tested in each specimen
Core sprayed with 3 coats of releasing agent	32 ± 4	3	3.5 S	4 spots tested in 1 specimen (5x13 in.)
Core sprayed with 1 coat of releasing agent	225 ± 35	3	3.5 S	4 spots tested in 1 specimen (5x13 in.)
Core soaked with releasing agent	270 ± 32	5	3.5 S	4 spots tested in 1 specimen (5x13 in.)
Core sprayed with soap			3.5S	4 spots tested in 1 specimen (5x13 in.)
Composite skin sprayed with WD-40 Oil			3.0 S	4 spots tested in 1 specimen (5x13 in.)
Plastic between core and adhesive			3.5 S	4 spots tested in 1 specimen (5x13 in.)
Cured at 260°F, 1 hour (90°F below normal cure temp.			No damage after 3.5 S of irrad.	3 spots tested in 1 specimen (5x13 in.)
Cured at 200°F, 3 coats of releasing agent on each side of adhesive			2.5 S (Debonds near the horned area) 5.0 S (More debonds)	3 spots tested in 1 specimen (5x13 in.)
Cured at 175°F; 3 coats of releasing agent on each side of adhesive			2.5 S (Debonds near the horned area) 5.0 S (Complete separation)	2 specimen (5x13 in.) 3 spots tested in each specimen
Cured at 175°F			2.5 S (No damage) 5.0 S (Complete separation)	3 spots tested in 1 specimen (5x13 in.)

BOND STRENGTH DETERMINATION.

In order to investigate the correlation between the input power level of high-power ultrasound and the bond strength of the specimens, compressive-shear or flatwise tensile tests were performed for each group of specimens.

The compressive-shear test was used for testing the bond strength of Type I specimens. As shown in Figure 1, Type I specimens were originally fabricated as 10x24 inch panels. These panels were machined into 1x10 inch strips. In each group, some of the strip specimens were used in the high power ultrasonic test and some were further machined into 0.5x1 inch compression specimens as shown in Figure 2. A total of about 2,000 compression shear specimens of the Type I configuration with various bonding conditions were tested. Average values of ultimate shear strength (load to failure) for each group of Type I specimens are listed in the second column of Tables 1 to 3. Some of the bonded panels, prepared with oil contamination on the bonding surfaces, were debonded during machining. The bond strength of these specimens was hence estimated to be smaller than the lowest value observed in our compressive shear test for Type I specimens, 2 KSI.

No compressive shear test was performed on Type II adhesively bonded composite/aluminum specimens due to a warped geometry of the bonded panels. The different thermal properties of the two materials plus their unbalanced stiffnesses caused the bonded panels to warp during the cool-down period after being extracted from the press.

A flatwise tensile test was conducted to obtain the bond strength of GrE/GrE specimens. It was found that in all cases the tensile failure was attributed to composite laminate failure instead of adhesive bond failure even in weak bond specimens.

In order to explain this abnormal result, it is necessary to examine the method of the flatwise tensile test. This kind of test is usually used for testing the tensile strength of honeycomb core reinforced sandwich specimens. Figure 3 shows a typical flatwise tension specimen and test block configuration. Both top and bottom surfaces of the test specimen were first adhesively mounted on the metallic test blocks which were then threaded into the tensile test machine. The ultimate tensile strength was obtained by dividing load-to-failure by the surface area of the specimen. It was later found that the adhesive used to bond the specimens on the flatwise test blocks was a high temperature adhesive. The specimen-test blocks assembly was cured at a temperature of 350^{o}F. Since our weak bond specimens were undercured, the specimens were further cured during the curing of the specimen-test blocks assembly, and therefore, the results of this test did not represent the true bond strength of the undercured GrE/GrE specimens. The bond strength of this type of spec-

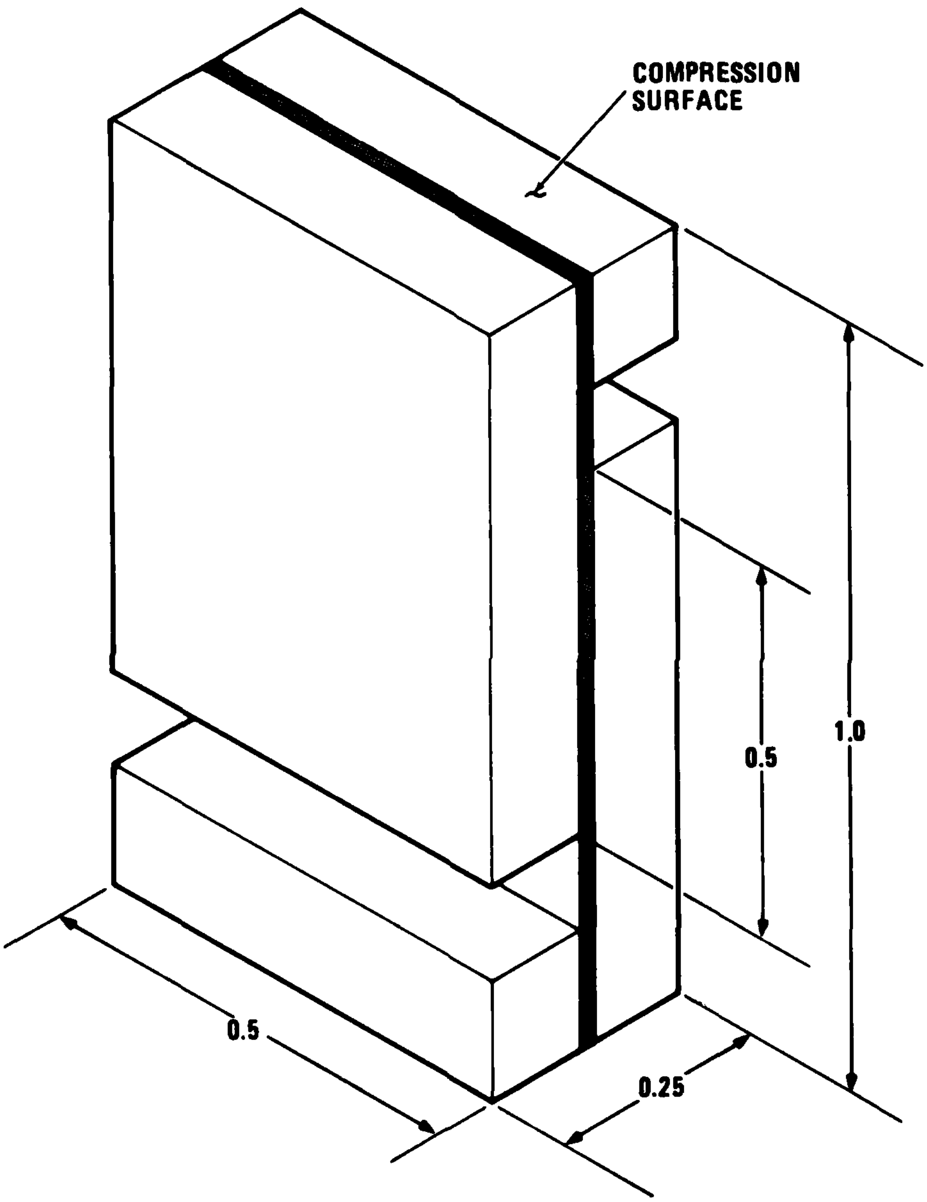


FIGURE 2 COMPRESSION SHEAR SPECIMEN

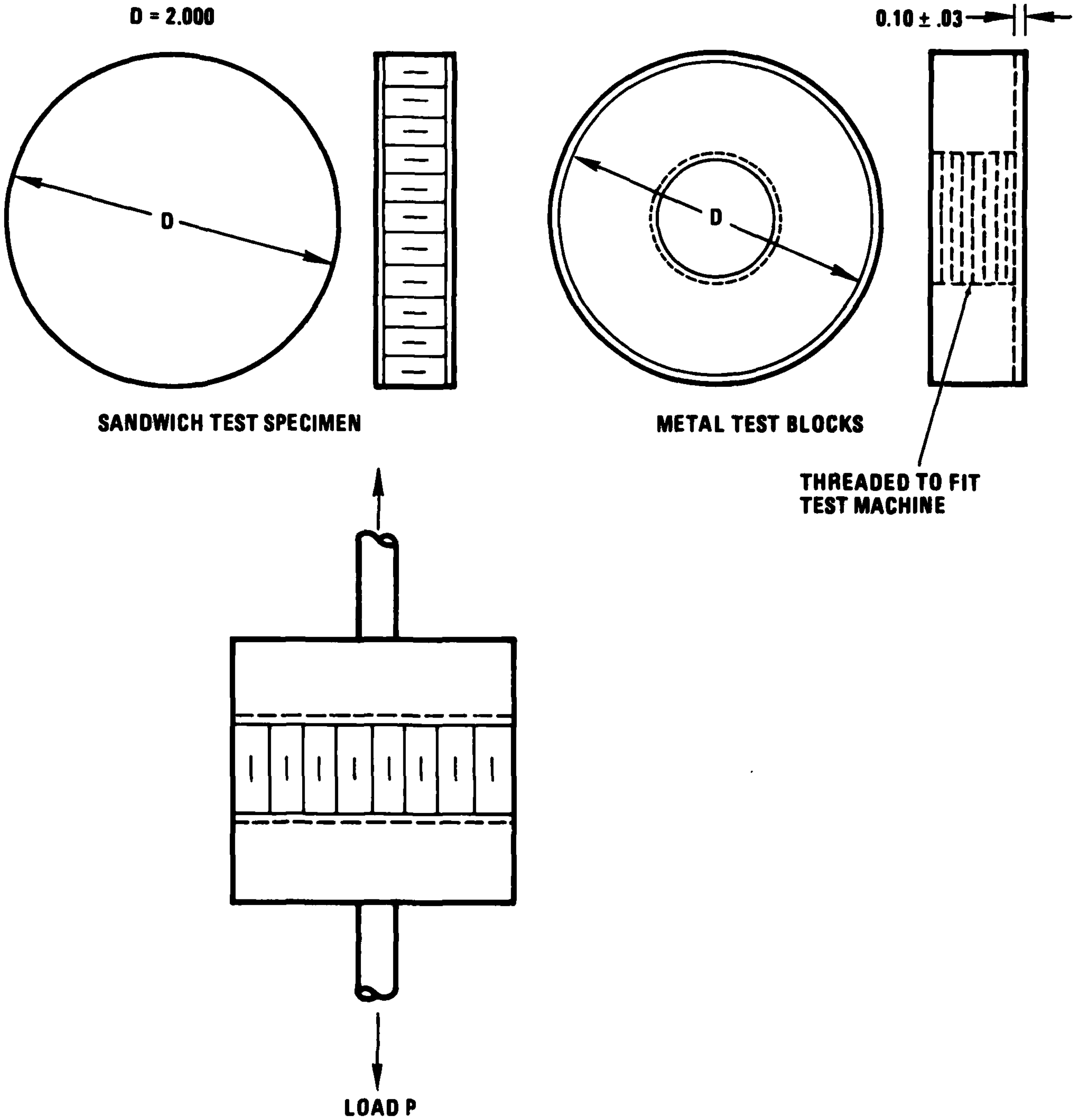


FIGURE 3 FLATWISE TENSION SPECIMEN AND TEST BLOCK CONFIGURATION

imen should be determined by other means.

The bond strength of Type III composite-honeycomb core reinforced sandwich specimens were determined by the flatwise tensile test. Three or more circular plugs (2-inch diameter) were cut from each specimen (4x10 inch) for utilization in the flatwise tensile test. A few strip specimens (1x10 inch) which were not suitable for flatwise tensile test were evaluated in the sandwich beam test.

HIGH-POWER ULTRASOUND (HPU) BOND STRENGTH SCREENING SYSTEM

PRINCIPLES OF THE HPU TECHNIQUE.

The high power ultrasonic (HPU) technique is based on sending pulses of 20 KHz high power ultrasonic waves into the test part. The stress waves generated by the high power ultrasound will disrupt and break weak bonds. Follow-up conventional pulse-echo ultrasonic inspection will detect the debonds created by the HPU irradiation.

The debonding mechanism under HPU irradiation is complicated. It is dependent on the types of weak bonds under irradiation. One type of weak bond commonly found is caused by bonding surface contamination by oil or other additives. Another type of weak bond is caused by undercure of the adhesive. In an area containing the first type of weak bond, there are many microstructural "defects", where the molecular bonds are either chemically or physically weak. During HPU irradiation, molecules at these micro-defect sites will vibrate with a larger displacement than the normal sites. The tensile stress combining with the shear stress due to high frequency mechanical vibration of the part will disrupt the weak bond area. In an area containing the second type of weak bond, the adhesive is not well cured. The under-cured adhesive absorbs more energy from the stress waves than the cured adhesive. The temperature increase at these areas during HPU irradiation will weaken the bond and disrupt the bonded area. Further discussions on the temperature effect will be given later.

HPU INSTRUMENTATION.

A block diagram of the high-power ultrasound (HPU) system is shown in Figure 4. A HPU system consists of three major components; a power supply, a converter-booster-horn assembly, and a control unit. The power supply provides high frequency (20 KHz) electrical energy to the converter which changes this energy into mechanical or vibratory energy. Coupled to the converter is a booster which determines the amplitude of vibration produced at the face of the horn. The purpose of the horn is to transfer the ultrasonic vibrations from the converter to the parts being tested. The control system controls the start and stop of HPU irra-

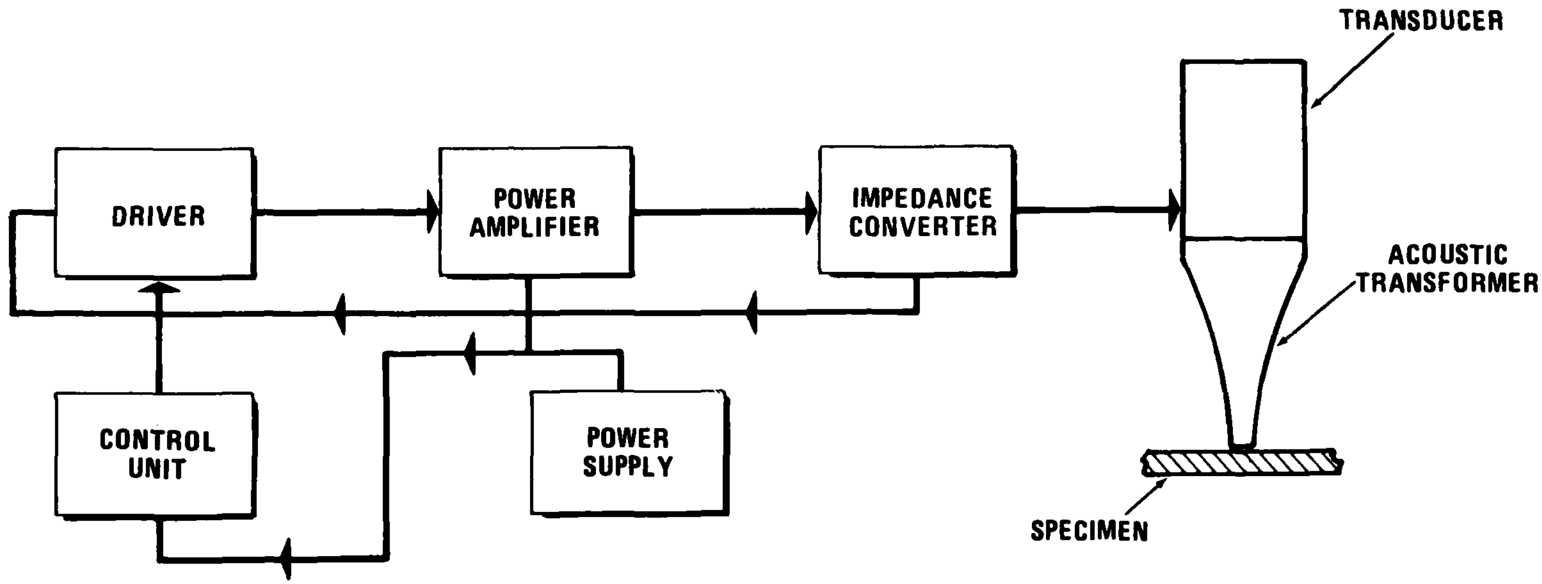


FIGURE 4 BLOCK DIAGRAM OF HPU SYSTEM

diation. It also displays the percentage of power which was actually loaded into the parts.

Two Branson ultrasonic power supplies were used in this program. One can provide 3000 electrical watts to the converter (2900 mechanical watts to load), and the other can provide 1700 watts to the converter (1640 watts to load). The output frequencies from both systems are the same, 20 KHz. The converter-booster-horn assembly can be mounted in a portable holder and operated manually by an operator remote from the power supply. It also can be mounted in a pneumatic-controlled actuator, which brings the horn in contact with the test specimen and activates the HPU at a predetermined pressure. Determination of a HPU power level for strip specimens was done by using the pneumatic-controlled unit. The portable system as shown in Figure 5 was used for evaluation of plate specimens. Figure 5 presents the power supply (1700 watts) and control unit (A), the converter-booster-horn assembly (B), and the test specimen (C), respectively. There are two starting switches mounted on the two handles (one on each side) of the horn assembly. The horn is spring loaded. The operator needs to apply a certain amount of pressure to bring the horn in contact with the specimen. The HPU will be activated as soon as both switches are pushed simultaneously. The HPU irradiation time is controlled by the control unit. The irradiation time can be set at any duration between 0.1 seconds to 6 seconds. A load meter on the control unit shows a percentage of power actually loaded into the specimen during HPU irradiation. In general, 40% of the power is loaded into the specimen when good coupling between the horn and the specimen is maintained.

HPU ENERGY LEVEL DETERMINATION.

The major objective of this program was to establish the HPU energy levels which will disrupt weak bonds but will not affect good bonds in adhesively bonded structures. Since in this system the power supply provides constant power output, the irradiation time is used to represent the level of energy absorbed by the specimen. Most of the tests were performed on strip specimens (1x10 inch) with the pneumatic-controlled high-power unit (3000 watts). Different kinds of specimen support were investigated, such as fixed-ends support, two-point hinged support, and simple solid support. It was found that the modes of support affected the actual power loading into the specimen. When a high level of power, e.g., 40% of the power, was loaded into the specimen, the HPU results were practically independent of the modes of support. Therefore, it is important for the operator to watch the load meter during HPU irradiation. The power loaded into the specimens with fixed-ends support and the two-point hinged support was very consistent, about 40%. The test data for each type of specimen is listed in Tables 1 through 8. The data will be discussed according to each type of specimen configuration. Minimum HPU energy levels required for screening weak bonds without damaging good bonds in each type of specimen are summarized at the end of this section.

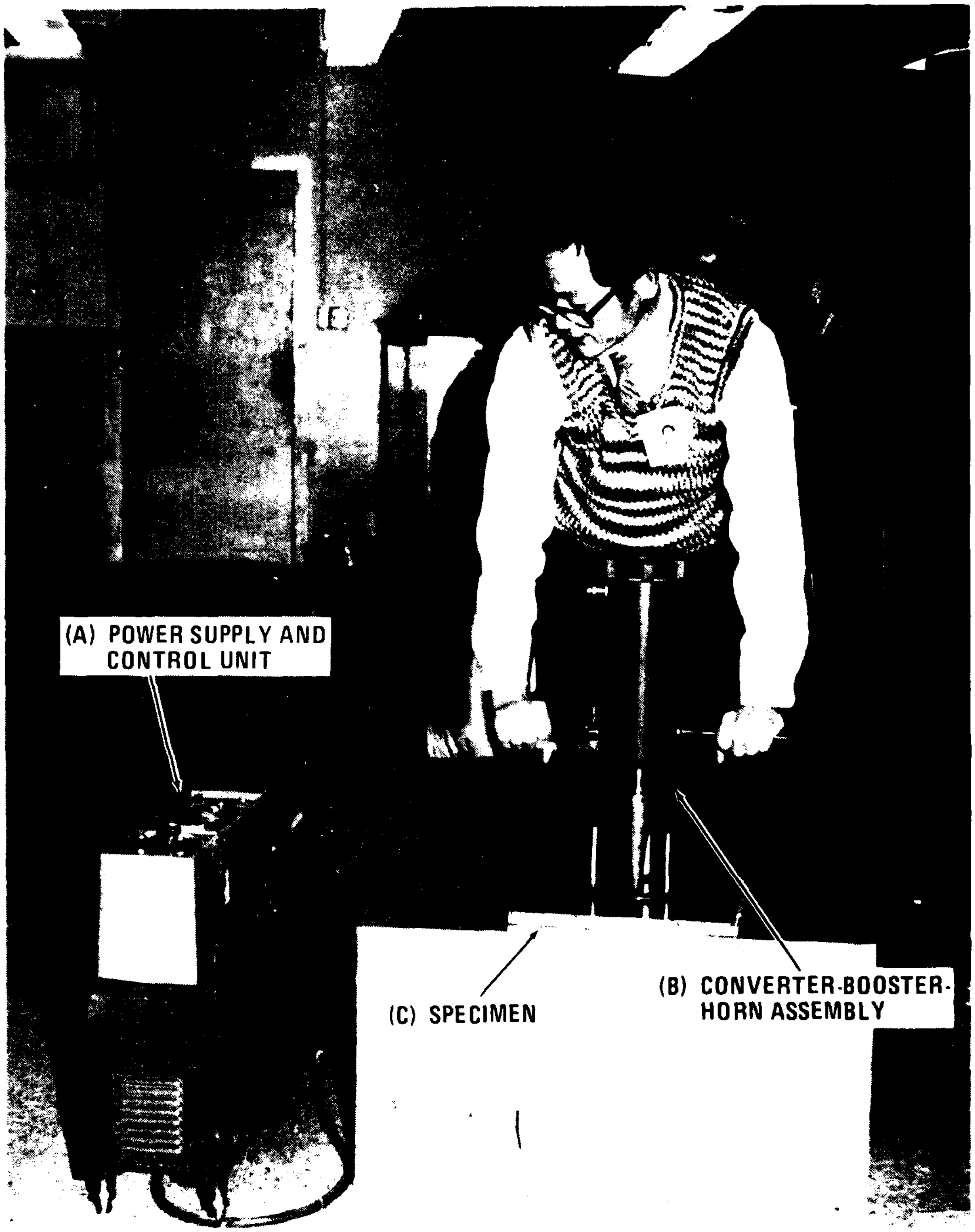


FIGURE 5 PORTABLE HPU BOND STRENGTH SCREENING SYSTEM

TYPE I SPECIMENS.

Al/Al Bonded with EA9649R Adhesive. The results for Type I specimens (Al/Al) bonded with EA9649R adhesive are shown in Table 1. These specimens were bonded according to a normal cure procedure but with different surface treatments prior to bonding. The results of the compressive shear test showed that the bond strength of these specimens can be divided into four groups. The control specimens (etched and cleaned) have an average ultimate shear strength of 12.3 ± 0.8 KSI. The unetched specimens have an intermediate bond strength of 10.3 ± 2.3 KSI. The specimens with the bond surface coated with WD-40 oil have a weak bond of 4.9 ± 0.5 KSI. The specimens with the bond surface coated with Frekote releasing agent have a very weak bond strength which was estimated to be less than 2 KSI. The average HPU irradiation time to induce debonds in the two groups with very weak and weak bond conditions is 0.3 seconds and 1.3 seconds, respectively. For the specimens with intermediate bond strength, it took an average of 4.8 seconds to induce small debonds. For the control specimens, after 10 seconds of irradiation, no observable damage was found. A compressive shear test was also performed on the control specimens after HPU irradiation. It was found that there is no difference in shear strength for the control specimens before and after HPU irradiation. The above results were based on tests of 1x10 inch specimens. Some 4x10 inch specimens were also tested and the results were similar to those of the 1x10 inch specimens.

Al/Al Bonded with AF147 Adhesive. The results for Type I specimens bonded with AF147 adhesive are shown in Table 2. The treatments of these specimens were similar to those bonded with EA9649R adhesive as described above. The ultimate shear strength for these specimens can also be divided into four groups: strong (9.4 ± 0.1 KSI), intermediate (8.6 ± 0.3 KSI), weak (4.8 ± 0.2 KSI), and very weak (<2 KSI) bonds. The average HPU irradiation time to induce debonds in the weak and very weak bond specimens was 2.6 seconds and 0.6 seconds, respectively. No damage was observed for the intermediate and strong bond specimens with irradiation time up to 7 seconds and 10 seconds, respectively. It is interesting to note that although the ultimate shear strength for specimens bonded with EA9649R adhesive was consistantly higher than the same type of specimens bonded with AF147 adhesive, more HPU irradiation time was required to induce debonds in specimens bonded with AF147 than those bonded with EA9649R.

Al/Al Bonded with FM300K Adhesive. The results for Type I specimens bonded with FM300K are shown in Table 3. The ultimate shear strength for etched specimens and unetched specimens was 11.2 ± 1.0 KSI and 7.1 ± 0.8 KSI, respectively. The average HPU irradiation time to induce debond in unetched specimens was 2.6 seconds. However, no damage was observed after 5 seconds of irradiation time on the etched specimens.

To find the correlation between ultimate shear strength and HPU irradiation time to induce debond in Type I specimens, ultimate shear strength versus HPU irradiation time have been plotted in Figure 6. The square represents the experimental point for Al/Al bonded with AF147. The circles and the triangle represent the data points for Al/Al bonded with EA9649R and FM300K, respectively. The ordinate of solid bars represents the ultimate shear strength which could not be debonded after HPU irradiated for a time indicated in the abscissa. Therefore, the solid bars set the high limit for the estimated correlation curves. The dashed curves (A) and (B) are the estimated correlation curves for Al/Al bonded with EA9649R adhesive and that bonded with AF147 adhesive, respectively. The data for specimens bonded with FM300K are similar to that of EA9649R. Although this is a rough estimate, it is important to know such correlation curves to assure that the power setting for screening weak bonds in a specimen will not affect the good bonds.

TYPE II SPECIMENS.

Composite/Composite Bonded with EA9649R Adhesive. The results for graphite/epoxy laminates bonded with EA9649R adhesive are shown in Table 4. The strong bonded specimens were cured at 350°F, the normal cure temperature for EA9649R. The weak bonded specimens were cured at a considerably lower temperature, 150°F. The average HPU irradiation time was 2 seconds for the thick panels (0.25 inch thick) and 1 second for the thin panels (0.125 inch thick). Debonds were found directly under the horned area. The failure was attributed to temperature increase at the bond line directly under the horn during HPU irradiation. Temperature measurements using an infrared camera were obtained for this type of specimens and the result will be discussed later. For the normal cured specimens, no damage was found after 10 seconds of HPU irradiation and no noticeable temperature increase was observed during irradiation. The result of the flatwise tensile test showed that the bond strength of the adhesive is stronger than that of GrE laminates. However, the flatwise tensile test did not reveal the correct bond strength for the undercured weak bond specimens for the reason discussed previously. Therefore, the quantitative correlation of the bond strength versus irradiation time cannot be obtained until more accurate bond strength tests are performed.

Composite/Al Bonded with EA9649R Adhesive. The results for GrE composite bonded to Al with EA9649R adhesive are shown in Table 5. Two groups of specimens were tested. One group of specimens was prepared with standard etched aluminum panels and the other group was prepared with unetched aluminum. The average HPU irradiation time to induce debond in the unetched specimens was 2 seconds if it was irradiated from the aluminum side. No damage was found after 4 seconds of irradiation when it was irradiated from the composite side. This difference could be due to the warped geometry of the specimens. Further investigation is needed to clarify this point. No damage was found in the etched

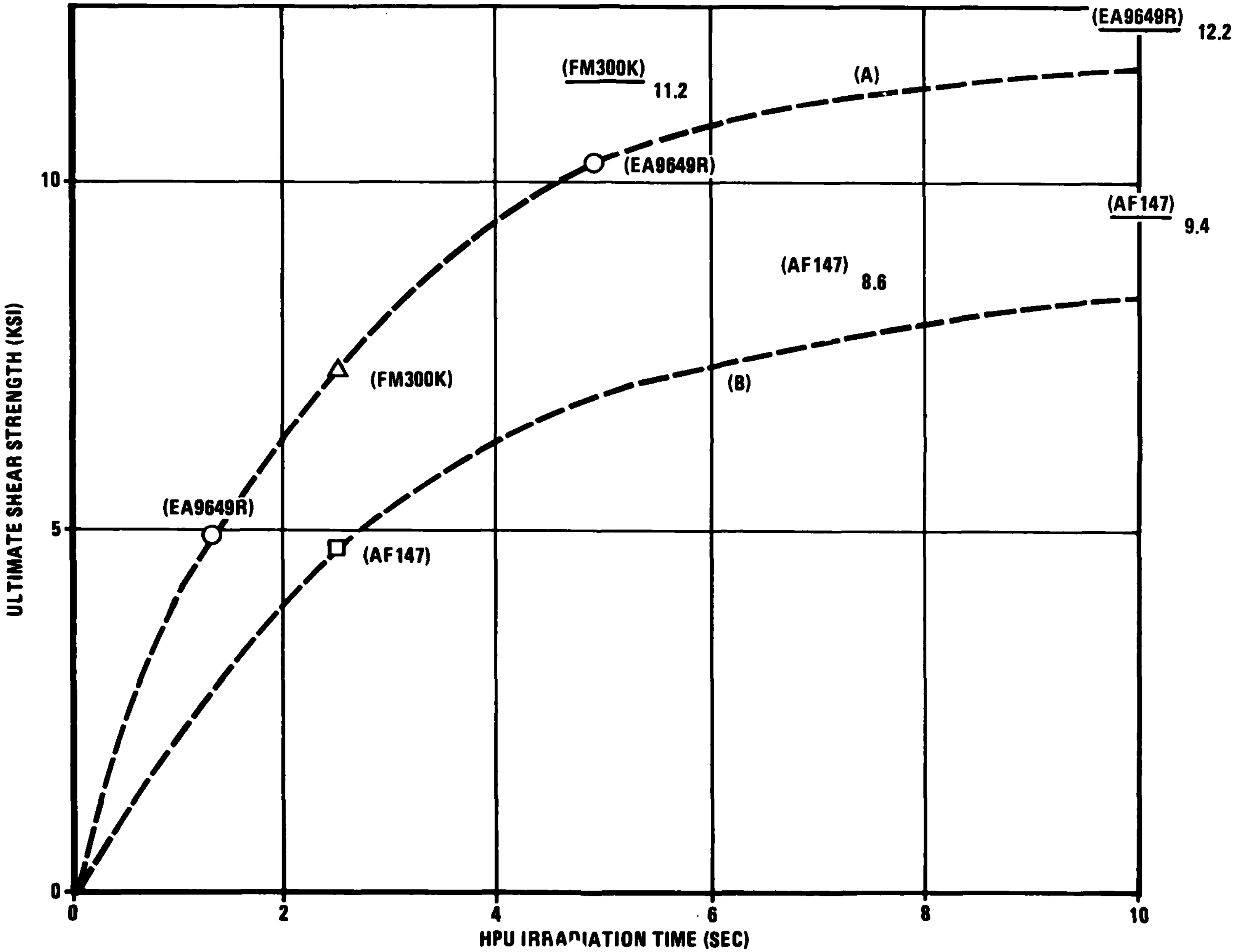


FIGURE 6 ULTIMATE SHEAR STRENGTH VS HPU IRRADIATION TIME FOR AL/AL SPECIMENS

specimens after 4 seconds of HPU irradiation from either the aluminum or the composite side of the specimens. The HPU results showed that the unetched specimens have weaker bonds than those of etched specimens. However, more experimental data from both HPU tests and bond strength tests are needed to draw a conclusive correlation between the bond strength and the irradiation time in this type of specimen.

<u>TYPE III SPECIMENS.</u>

<u>GrE/Al Honeycomb/Al Bonded with EA9649R Adhesive</u>. The results for GrE/Al Honeycomb/Al specimens are shown in Table 6. The weak bond specimens were prepared by spraying a coat of WD-40 oil on the honeycomb core surface to be bonded on the GrE composite skin. The specimen was irradiated by HPU from the composite skin. The irradiation time to induce debond between the composite skin and the core was 1 second. Another specimen bonded with a bad adhesive was also debonded with 1 second of HPU irradiation. The ultimate tensile strength of these two specimens was between 400-500 PSI as determined from the flatwise tensile test. No debond was observed in the good specimens, which were prepared with normal procedures and having ultimate tensile strength of 745 $\pm$ 163 PSI, for up to 5.2 seconds of HPU irradiation. However, damage to the honeycomb core was noticed after 5.2 seconds of irradiation. Two good specimens were soaked in water for 15 days prior to the HPU test. It was expected that the bond strength of the specimens would be weakened by moisture. However, no debond was observed, but core damage was observed after 4 seconds of HPU irradiation. Two other specimens which were exposed in 95% relative humidity at 150°F for 15 days before the HPU test also showed the same result. Since these two groups of specimens were 1x10x1 inch strips, the sandwich beam test was used to test the core shear stress. The ultimate core shear strength was found to be about 300 PSI for test specimens.

<u>Al/Nomex Honeycomb/Al Bonded with AF147 Adhesive</u>. Two specimens of Al/Nomex Honeycomb/Al bonded with AF147 adhesive were prepared according to a normal procedure. The ultimate tensile strengths from the flatwise test for these two specimens were 905 $\pm$ 102 PSI and 1106 $\pm$ 85 PSI. The HPU irradiation time to induce debond in these two specimens were 1.3 seconds and 2.6 seconds, respectively, as shown in Table 7. Although the ultimate tensile strength of this group of specimens was stronger than that of composite/Al Honeycomb/Al specimens, the HPU energy level required to debond this group of specimens was much less than that to debond composite/Al honeycomb/Al specimens. This can be attributed to the different attenuation coefficients of ultrasonic stress waves in the Al skin and in the composite skin. The Al skin absorbs much less of the ultrasonic energy than the composite skin, and hence the HPU is more effective in debonding honeycomb core specimens with an aluminum skin than those with a composite skin.

GrE/Nomex Honeycomb/Al Specimens Bonded with EA9649R Adhesive. The results for GrE/Nomex Honeycomb/Al specimens bonded with EA9649R adhesive are shown in Table 8. All of these specimens were prepared with weak bond conditions between the GrE skin and the honecomb core, and the HPU was irradiated from the GrE side. One group of specimens was prepared by spraying additives, such as Frekote™ releasing agent, WD-40, and soap, on the surface of the core and/or the surface of the composite skin just prior to bonding. Another group was prepared with surface contamination and also by curing the specimens at a lower curing temperature. The ultimate tensile strength of the first group of specimens measured by the flatwise tensile test ranged from 32 to 270 PSI. The average HPU irradiation time to induce debond in these specimens was found to be practically the same, about 3.0 to 3.5 seconds. The average irradiation time for the group with surface contamination and also under-cured at lower temperatures was 2.5 seconds. Two additional specimens were cured at 175°F and 260°F without surface contamination. The average HPU irradiation for the one cured at 175°F was 2.5 seconds and no damage was found for the one cured at 260 F after 5.0 seconds of irradiation. The ultimate tensile strength for the control specimens (contamination free and well-cured) was about 1600 PSI which is about 5 times higher than that of the weak bonded specimens tested. No debond was observed in the control specimen when subjected to HPU irradiation for up to 10 seconds, however, damage in the core was found after 10 seconds of irradiation. From the above results, 3.5 seconds of HPU irradiation time should be sufficient to screen weak bond conditions and do no damage to the good bonds in this type of specimen.

From the above results, the HPU irradiation times required to screen weak bonds but which will not affect good bonds in Type I, II, and III specimens are summarized in Table 9 and discussed as follows.

(1) For Al/Al specimens, 2.6 seconds of HPU irradiation will screen weak bond conditions due to improper preparation of bonding surfaces, such as unetched and contamination of oils, etc., and will not degrade good bonds.

(2) For composite/composite specimens, 2.0 seconds of HPU irradiation will disrupt weak bonds due to under-cured conditions but will not damage the normally-cured adhesive bond. As for composite/Al structure, current data are not sufficient for making any conclusive determination of HPU power level. More data are needed in this area.

(3) For Al honeycomb core with composite skin structure, 1 second of HPU irradiation will disrupt weak bonds due to bad adhesive or contamination of oils on bonding surfaces. (4 seconds of irradiation will damage Al core).

(4) For Nomex honeycomb core with composite skin structure, 3.5

seconds of HPU irradiation will screen weak bonds due to surface contamination and under-cured conditions. (10 seconds of irradiation will damage Nomex core).

(5) For Nomex honeycomb core with Al skin structure, 1.3 seconds of HPU irradiation will disrupt weak bonds due to bad adhesive. However, only 2.6 seconds of irradiation is needed to disrupt good bonds. Further investigation in this type of structure is needed.

TABLE 9 SUMMARY OF HPU POWER LEVEL TO SCREEN WEAK BONDS WITHOUT DAMAGE GOOD BONDS

Structure*	Adhesive	Good Bond Condition	Weak Bond Condition	HPU Power Selection (Irrad. Time in Sec.)
Al/Al	EA9649R	12.3 KSI (Shear test)	4.9 KSI (Due to surface contamination)	1.3 (No damage to good bond up to 10 sec of irrad.)
	AF 147	9.4 KSI (Shear test)	4.8 KSI (Due to surface contamination)	2.6 (No damage to good bond up to 10 sec of irrad.)
	FM 300K	11.2 KSI (Shear test)	7.1 KSI (Due to unetched surface)	2.6 (No damage to good bond up to 5 sec of irrad.)
GrE/GrE	EA9649R	Standard cure and surface preparation	Adhesive under-cured	2.0 (No danage to good bond up to 10 sec of irrad.)
Al H/C core GrE skin	EA9649R	Standard cure and surface preparation	Surface contamination	1.0 (Damage in core at 4 sec)
Nomex H/C core, GrE skin	EA9649R	Standard cure and surface preparation	Under-cure; surface contamination	3.5 (Damage in core at 10 sec)
Nomex H/C core, Al skin	EA9649R	1106 PSI (Tensile test)	905 PSI (Bad adhesive)	1.3 (2.6 sec will damage good bond)

* Thickness of Al and GrE skins ~ 1/8 - in.

EVALUATION OF SELECTED STRUCTURES

Al/Al BONDED PLATE.

Two 18x18x0.25 inch Al/Al bonded plates prepared for other programs were obtained for evaluation. One plate was a control (good bond) specimen and the other was prepared without proper surface cleaning. Both plates were bonded with RB398 adhesive. Each plate was irradiated with HPU at 5 positions, (A, B, C, D and E) as indicated in Figure 7. Each position was irradiated for 5 seconds. Before and after the HPU irradiation, a pulse-echo ultrasonic technique was used to inspect debonds. After HPU irradiations, the plates were then machined into 1x18 inch strips and then cut into 1x0.5 inch compression shear specimens to test the bond strength of the individual specimen. Each specimen was labeled in a grid pattern on the original 18x18 inch plate. In this way we can evaluate the two-dimensional (2D) effect of high power ultrasonic irradiation on plate specimens.

For the good bond specimen, no debond was observed using the pulse-echo technique after HPU irradiations. In Figure 7, average ultimate shear strength at 9 areas, including 5 irradiated and 4 unirradiated areas, is shown for comparison. Areas A, B, C, D and E are irradiated areas and areas I, II, III and IV are unirradiated areas. The number indicated in each area represents the average ultimate shear strength (in KSI) of the 21 specimens in the area. The results show no difference in bond strength at the irradiated and unirradiated areas. This strongly suggests that at the selected power level the HPU will not affect the good bond.

For the plate with weak bond conditions, before HPU irradiation, no debond was observed using the pulse-echo ultrasonic technique. After HPU irradiation, a large debond was found near the area E, shown in Figure 7 (B). After the compression shear test, it was found that in one area near E, (circled by a dashed lines in Figure 7 (B), the color of the adhesive appeared to be different from the remaining area. Also the compression shear strength at that area was particularly low. The HPU system successfully screened out that contaminated area and did not weaken the bond strength at other areas.

REPAIRED HONEYCOMB STRUCTURES.

Repaired honeycomb structures, GrE/Al honeycomb core/GrE, were fabricated with different cure processes to generate weak bond conditions. A cross-section of the core-plug skin-patch repaired panel is shown in Figure 8. A core-plug with 2.5 inch diameter was bonded in the center of a 10x10 inch honeycomb structure. A skin-patch with 4.5 inch in diameter was bonded on the top of the core-plug and the upper skin of the panel. FMS-3018 adhesive was used for bonding. A standard repaired panel, cured at the normal

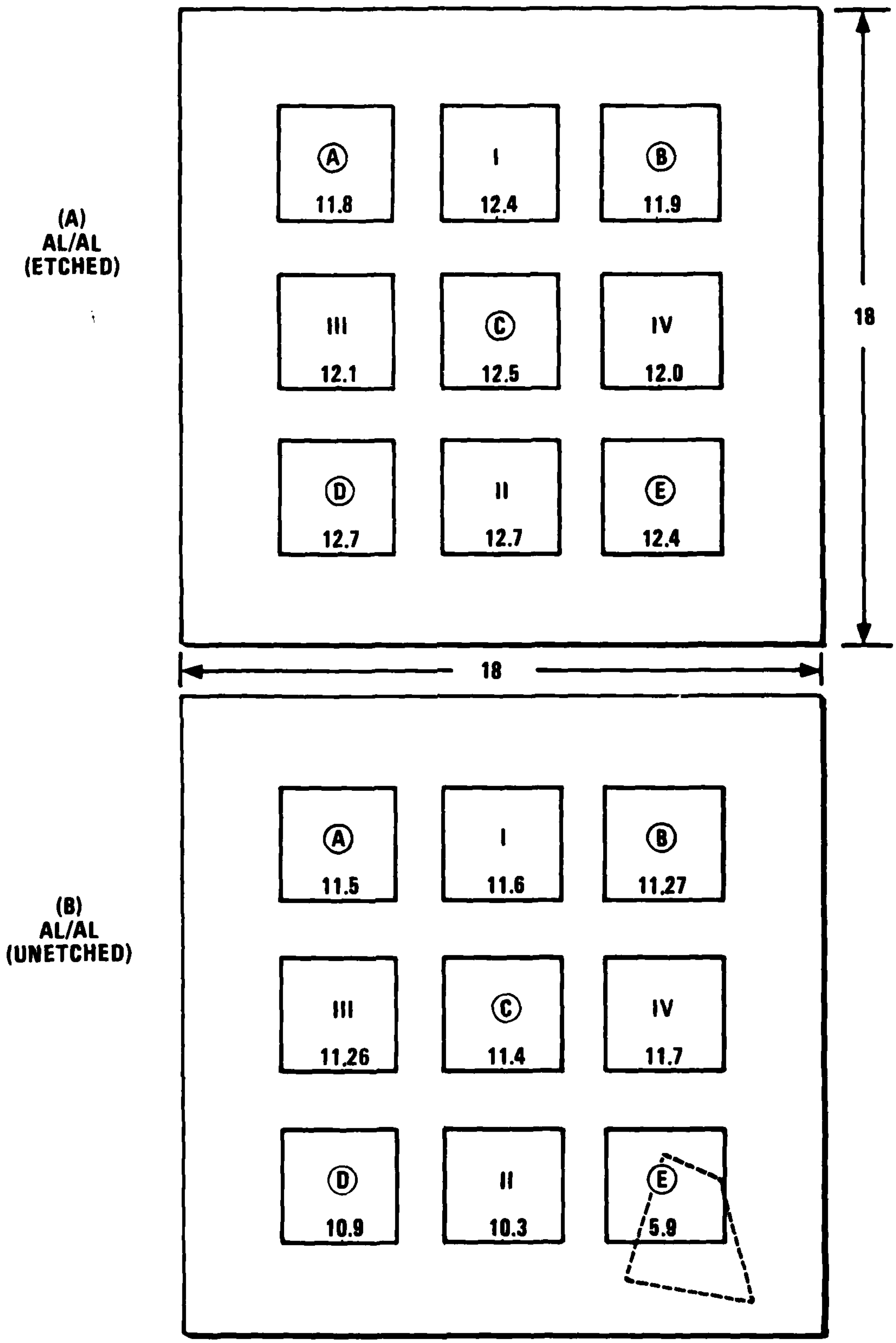


FIGURE 7 HPU TEST ON AL/AL PLATES: (A) ETCHED AND (B) UNETCHED

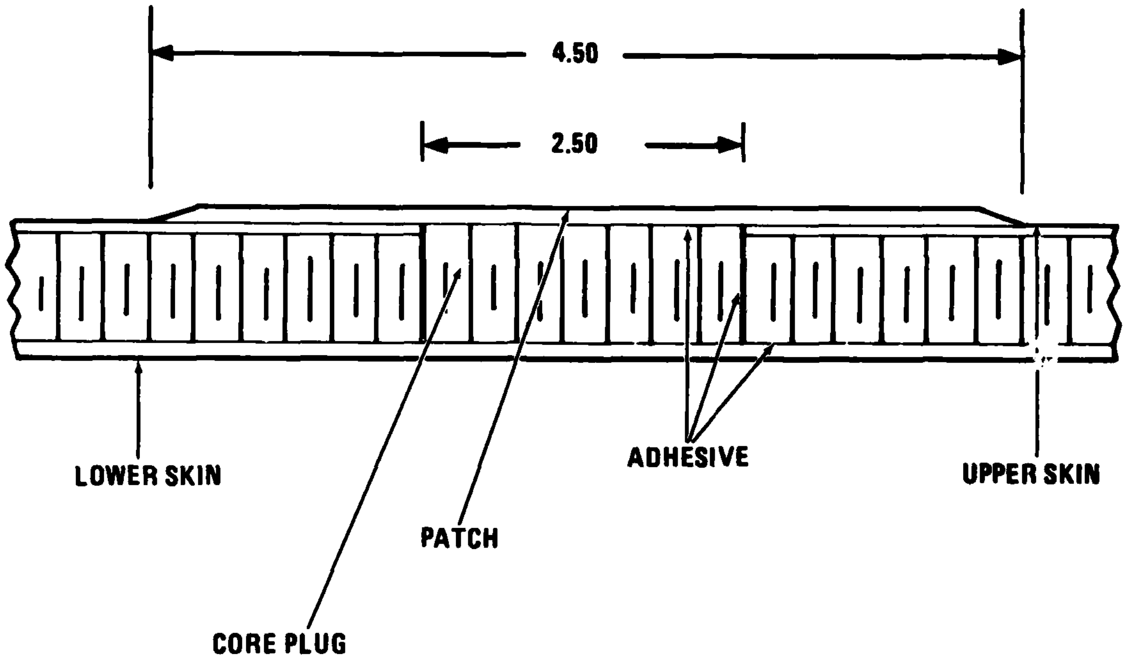


FIGURE 8 CROSS SECTION OF TYPE III REPAIRED SPECIMEN

TABLE 10 TEST RESULTS OF TYPE III (GrE/Al Honeycomb/GrE) REPAIRED SPECIMENS BONDED WITH FMS 3018 ADHESIVE

Fabrication Treatment	Bond Condition	HPU Test (Horn impact on the center of the patch-skin directly above the core plug)
2.5" diameter core plug skin patch repaired (See Fig. 8); Cured at 300°F	Good bond for core plug-skin patch repair	No damage after 2.0 S of irradiation
Two-stage cure process: 300°F for upper skin and 150°F for lower skin	Good bond between core plug and patch skin; Poor bond between core plug and inner surface of lower skin	No damage after 2.0 S of irradiation
Cured at 150°F	Poor bond between core plug and patch skin	Debond under the horn area after 1.0 S of irradiation

cure temperature of 300^{o}F, represented the good bond for the core-plug skin-patch repair. A second panel was cured in two stages: 300^{o}F for the upper skin and 150 F for the lower skin, producing a good bond between the core-plug and the skin-patch but a weak bond between the core-plug and the inner surface of the lower skin. The third panel was cured at 150^{o}F representing a weak bond between the core-plug and the skin-patch.

All three panels were irradiated by HPU on the center of the skin-patch. The result is summarized in Table 10. One second of HPU irradiation on the third panel induced a debond between the skin-patch and the core-plug directly under the irradiated area. Pulse-echo ultrasonic inspections before and after HPU irradiation are shown in figures 9 and 10, respectively. The circle in Figure 9 and again in Figure 10 represents the area (the repaired core-plug) inspected by the In-Service Inspection System (ISIS). The dark area inside the circle in Figure 10 shows debonds between the skin-patch and the core-plug which were created by HPU after 1.0 second of irradiation. The same power level did not affect the bonding between core-plug skin-patch of other two panels. Increasing the irradiation time to 2.0 seconds still would not affect the bonding of these two panels. Since HPU was applied to the upper skin side, the weak bond between the core-plug and inner surface of the lower skin of the second panel was not affected.

The aforementioned tests demonstrate the feasibility of the HPU system for use as an NDI tool to screen weak bonds in repaired honeycomb structures.

ANALYTICAL STUDIES OF HPU EFFECTS ON BONDED STRUCTURES

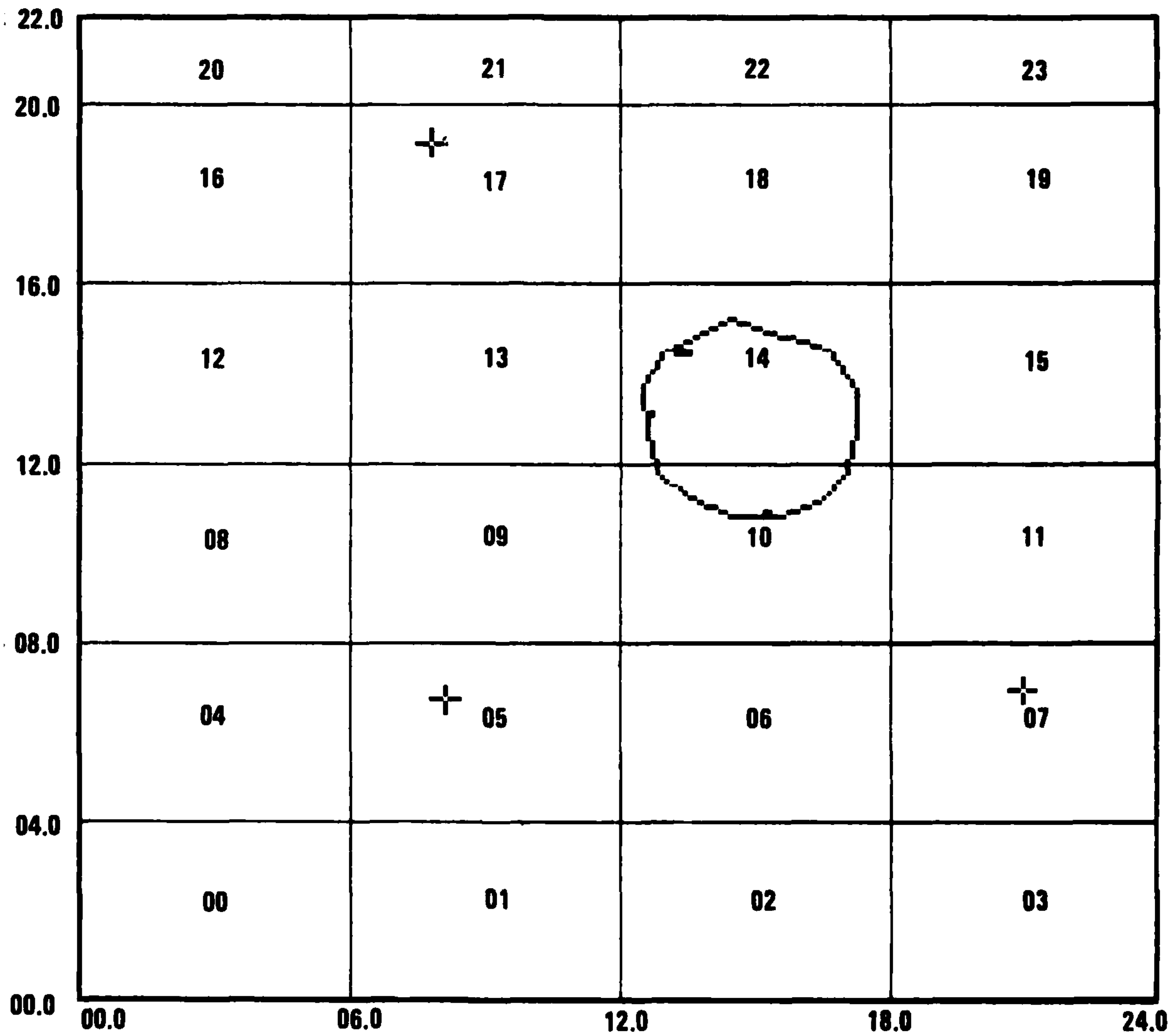
HPU EFFECTS ON ONE-DIMENSIONAL (1D) TEST SPECIMEN.

Our analytical effort started with a simple strip specimen of Al/Al which can be considered as a one-dimensional (1D) specimen. The specimen consisted of two pieces of Al 1x10x0.125 inch which were adhesively bonded. Since the bondline was very thin (~5 mils), the attenuation of sound waves due to the adhesive was neglected for the initial analytical calculation.

Assuming a HPU horn exerts a vertical sinusoidal load at the middle of a beam specimen, as shown in Figure 11, the sinusoidal load will force the beam into vibration. Since in the 1D specimen (1x10x0.25 inch), the cross section of the beam is much smaller than the length of the beam, the deflection is calculated by using elementary beam theory which would be a good approximation in this simple 1D specimen. From the calculated displacement amplitude of the beam, the vertical shear at a cross section of the beam as well as the maximum shearing stress at the center line (the bondline) can be estimated.

1. LOCATION GD/FT WORTH
2. INSPECTOR S.Y.C.
3. DATE/TIMER READING 5-27-83
4. ACFT TYPE/TAIL NO. FAA TYPE 3
5. PART NAME/SERIAL NO. REPAIR 7C
6. UNIT NO. – SKIN NO. COMP-AL H/C-COMP
7. TAPE RECORD NO. 010
8. CELL SIZE SQ = .2

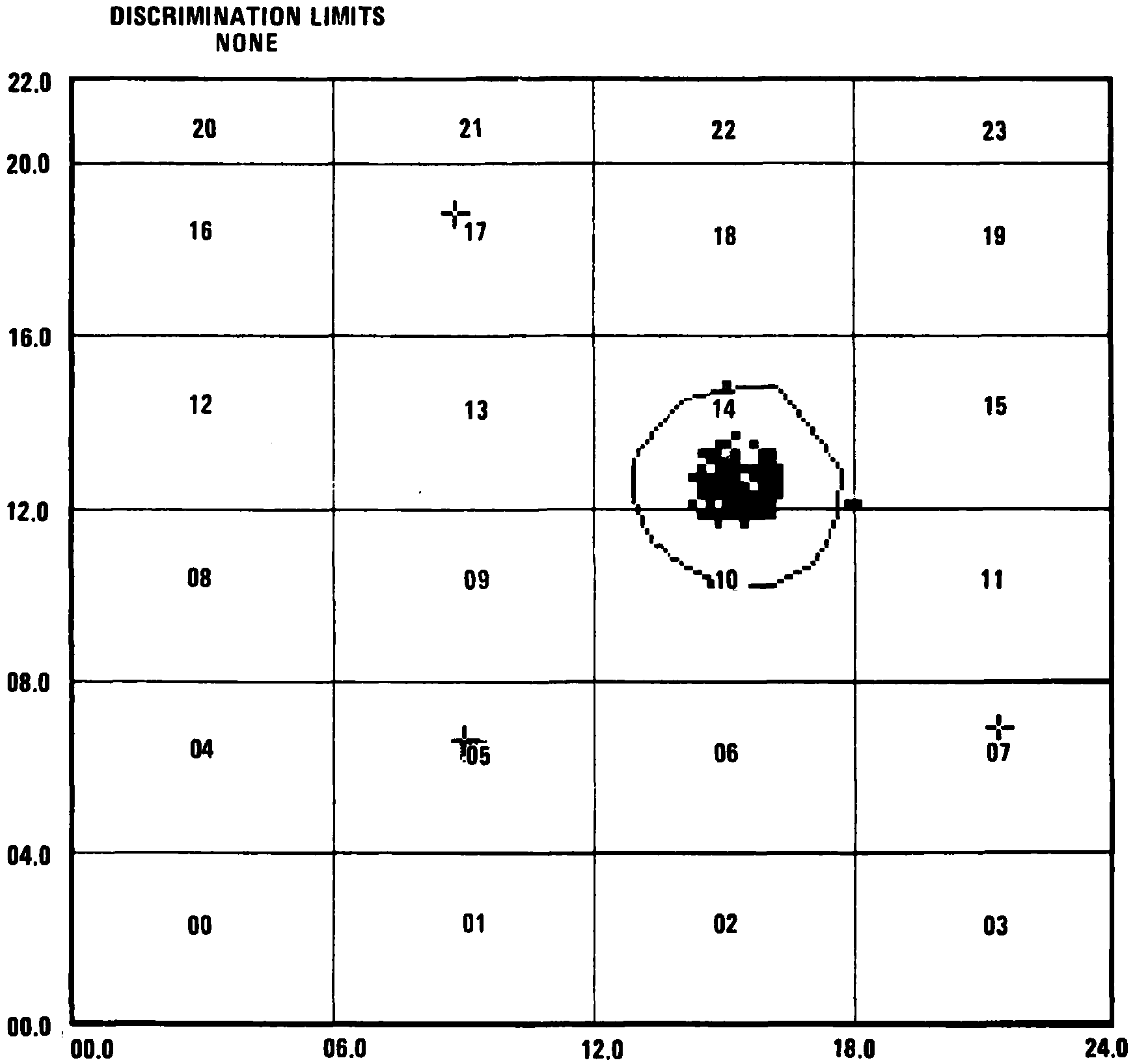
DISCRIMINATION LIMITS
NONE



TARGET POINTS
X = 07.8, Y = 19.1
X = 08.1, Y = 06.7
X = 20.9, Y = 06.9

FIGURE 9 PULSE-ECHO ULTRASONIC INSPECTION OF REPAIRED HONEYCOMB SPECIMEN NO. 3 BEFORE HPU IRRADIATION

1. LOCATION GD/FT WORTH
2. INSPECTOR S.Y.C.
3. DATE TIMER READING 5-27-83
4. ACFT TYPE TAIL NO. FAA TYPE 3
5. PART NAME SERIAL NO. REPAIR 7C HORNED
6. UNIT NO. – SKIN NO. COMP-AL H/C-COMP
7. TAPE RECORD NO. 011
8. CELL SIZE SQ = .02



TARGET POINTS
X = 08.8, Y = 18.8
X = 09.0, Y = 06.6
X = 21.3, Y = 06.9

FIGURE 10 PULSE-ECHO ULTRASONIC INSPECTION OF REPAIRED HONEYCOMB SPECIMEN NO. 3 AFTER HPU IRRADIATION

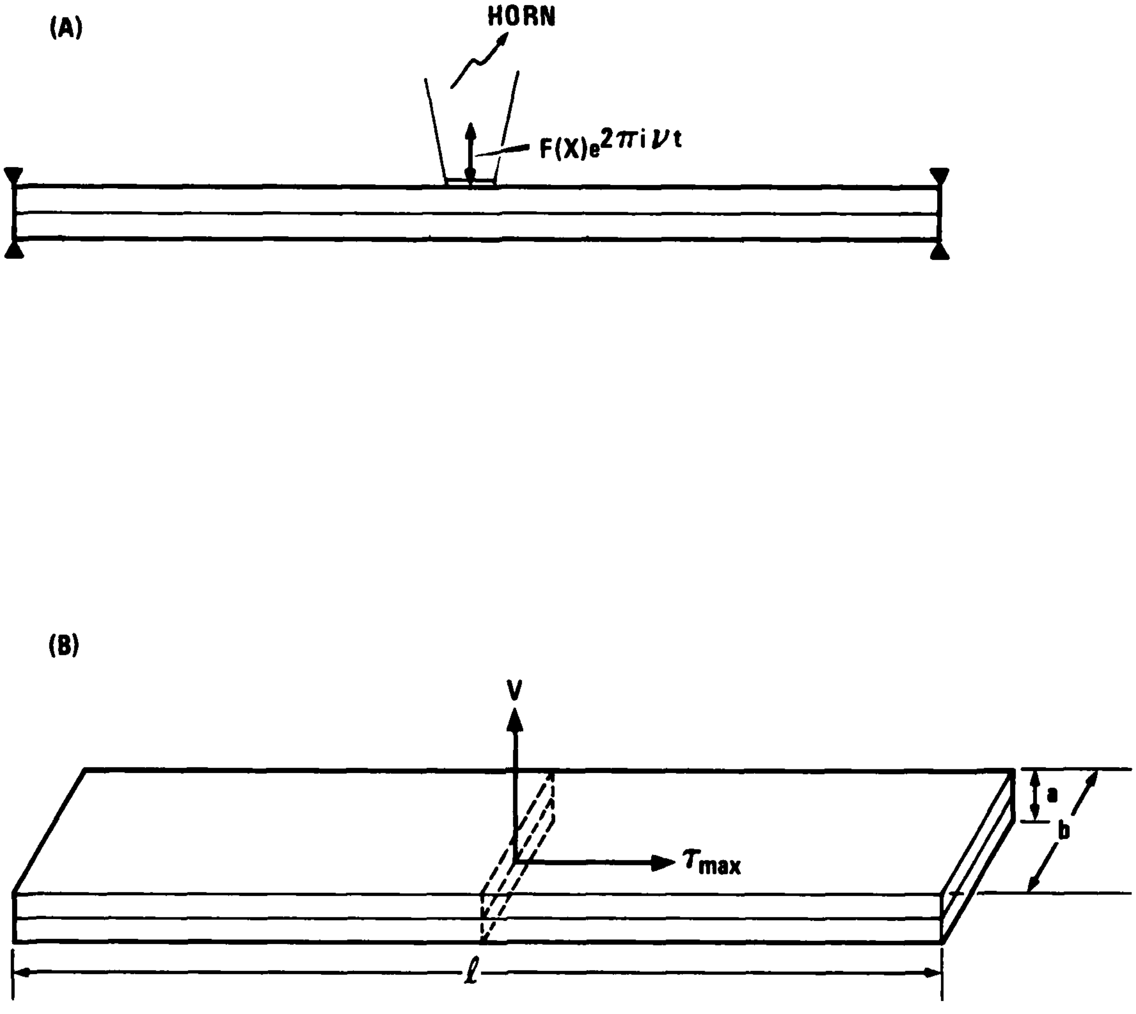


FIGURE 11 ILLUSTRATION OF ONE-DIMENSIONAL (1D) TEST SPECIMEN

The equation of motion of a beam driven by a sinusoidal force f(x,t) can be derived as

$$EI \frac{\partial^4 y(x,t)}{\partial x^4} + \rho A \frac{\partial^2 y(x,t)}{\partial t^2} = f(x,t)$$

where EI is the modulus of flexual rigidity, ρ is the volume density, and A is the cross section area of the beam.

The applied load is sinusoidal in time specified by

$$f(x,t) = F(x)e^{i\omega t}$$

where $\omega = 2\pi\nu$ and ν is the frequency of the HPU. Since the load is sinusoidal, we assume that

$$y(x,t) = Y(x)e^{i\omega t} .$$

The time-independent equation of motion can be obtained as

$$\frac{d^4 Y(x)}{dx^4} - k^4 Y(x) = \frac{F(x)}{EI}$$

where $k^4 = \rho A \omega^2 / EI$.

The equation can be solved by using a standard method and the solution is as follows.

$$Y(x) = \frac{1}{EI} \sum_{n=o}^{\infty} \frac{g_n}{k_n^4 - k^4} \psi_n(x)$$

where

$$g_n = \frac{2}{\ell \rho A} \int_o^{\ell} F(x)\psi_n(x)dx$$

$$K_n^4 = \rho A \omega_n^2 / EI, \quad \omega_n = 2\pi\nu_n , \quad n = 1,2,3,.........$$

$\nu(x)$ is the allowed natural frequency, and

$$\psi(x) = a \cosh k_n x + b \sinh k_n x + c \cos k_n x + d \sin k_n x$$

values of k_n and coefficients a, b, c, and d can be evaluated according to the boundary conditions. Three common types of boundary conditions are (1) fixed-end, (2) free beam, and (3) hinged-end (simple two-end support).

The wave function $\psi_n(x)$ for these three boundary conditions are shown as follows.

(1) Fixed-end: ($\psi = \psi' = 0$ at both ends)

$$\psi_n(x) = \begin{cases} \frac{1}{\sqrt{2}} \left[\cosh k_n x - \sinh k_n x - \cos k_n x + \sin k_n x\right], & \text{for } 0 \le x \le \frac{\ell}{2} \\ \frac{1}{\sqrt{2}} \left[\cosh k_n(\ell-x) - \sinh k_n(\ell-x) - \cos k_n(\ell-x) + \sin k_n(\ell-x)\right], & \text{for } \frac{\ell}{2} \le x \le \ell. \end{cases}$$

where

$$k_n = \frac{\pi}{\ell}\beta_n \quad \left(\text{ and } \nu_n = \frac{\pi}{2\ell^2}\sqrt{\frac{EI}{\rho A}}\,\beta_n^2\right)$$

$$\beta_n \simeq n + \tfrac{1}{2}, \quad n = 1,2,3.......$$

(2) Free beam: ($\psi'' = \psi''' = 0$ at both ends)

$$\psi_n(x) = \begin{cases} \frac{1}{\sqrt{2}} \left[\cosh k_n x - \sinh k_n x + \cos k_n x - \sin k_n x\right], & \text{for } 0 \le x \le \frac{\ell}{2} \\ \frac{1}{\sqrt{2}} \left[\cosh k_n(\ell-x) - \sinh k_n(\ell-x) + \cos k_n(\ell-x) - \sin k_n(\ell-x)\right], & \text{for } \frac{\ell}{2} \le x \le \ell. \end{cases}$$

where allowed values of k_n and ν_n are the same as for the fixed--end condition.

(3) Hinged-end: ($\psi = \psi'' = 0$ at both ends)

$$\psi_n(x) = \sin k_n x$$

where:

$$k_n = \frac{\pi}{\ell}n \quad \left(\text{ and } \nu_n = \frac{\pi}{2\ell^2}\sqrt{\frac{EI}{\rho A}}\,n^2\right)$$

$$n = 1,2,3,.......$$

Once the displacement of the beam Y(x) is known, the vertical shear (V) at any cross section and the maximum shearing stress at the center plane (bond line) of the beam specimen can be estimated using the following formula:

$$\text{The vertical shear } V(x) = -EI \frac{\partial^3 Y(x)}{\partial x^3}$$

$$\text{The maximum shearing stress } \tau_{max} = \frac{3V}{2A}$$

A sample calculation for a 1x10x0.25 inch Al specimen with a fixed-end boundary condition will be given as follows:

The sound intensity from the Branson high power ultrasonic horn is estimated at about 1017 W/cm^2. However, experimentally, only 30% to 40% of the power is loaded into the specimen. The effective pressure is estimated at about 8×10^7 dyne/cm^2. Using the modulus of flexual rigidity EI = 3.8×10^{10} dyne/cm^3 and density ρ = 2.7 g/cm^3 of the Al beam, we obtain the displacement Y(x), which is shown in Figure 12. The maximum displacement amplitude of the beam is $Y_o = 4.8 \times 10^{-3}$ cm.

The maximum vertical shear and the maximum shearing stress, as illustrated in Figure 11 (B), are also estimated to be $V_{max} = 1.5 \times 10^8$ dyne (at Y(x) = 0) and $\tau_{max} = 3V_{max}/2A = 1.4 \times 10^8$ dyne/cm^2 = 2032 PSI.

The value of τ_{max} calculated from the beam theory can only be considered as a first approximation since the specimen was assumed to be isotropic and homogeneous. Energy loss during wave propagation was also neglected. In actual bonded structures, many factors, such as anisotropy, inhomogeneity and energy loss can no longer be neglected and the ultrasonic stress waves cannot be treated as linear elastic waves. However, from the above study, we observed that the maximum displacement occurs under the horned area. If we move our focus on a 2D structure instead of a strip specimen and also consider the energy damping effect, we can foresee that the only significant displacement would be near the horned area. Therefore, the effect of HPU on the structure would be a localized one. Some of our tests on 2D specimens seem to support this postulate. An analytical model based on the localization phenomenon should be more practical because boundary conditions of the test structure are no longer a major factor.

FINITE-ELEMENT STRESS ANALYSIS AND STRAIN RESPONSE MEASUREMENTS.

In the previous analytical model, the thin adhesive layer in the bonded specimen was neglected. Another model was developed to include the adhesive layer in the analytical calculation. The approach is described as follows.

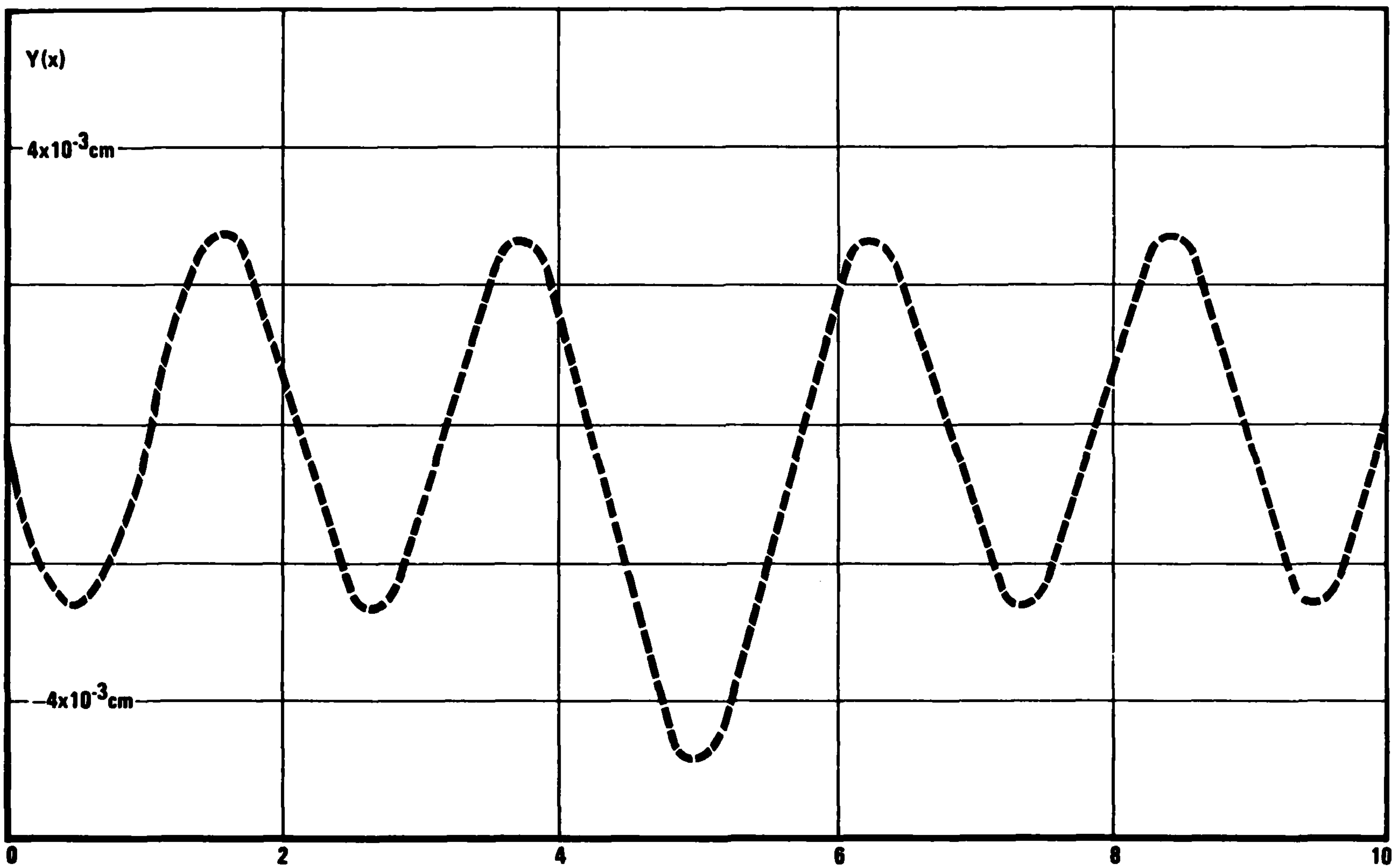


FIGURE 12 CALCULATED DISPLACEMENT Y(x)

A NASTRAN finite-element computer program modeling a 3-layer one-dimensional specimen was utilized to compute normal modes and stresses of the specimen in the frequency range from 0 to 20 KHz. The modeled specimen consisted of two Al beams measuring 1x10x0.125 inch bonded together on their flat sides with EA9649R adhesive. The adhesive bond thickness was assumed to be a uniform 5-mil thickness. Only one half of the beam was modeled because it is symmetrical about the longitudinal centerline. The specimen was clamped at 1 inch from both ends. Solid elements were used for the bondline as well as for the aluminum plates. Each layer consisted of a single row of 20 equal elements. A total of 17 normal modes, including 7 vertical bending modes were computed in the frequency range of interest. Normal and shear stresses were computed for the geometric center and each corner point of each element due to each vertical bending mode. Since the above computed stresses were only relative values, an attempt was made to quantify the computed stresses using experimental data from strain response measurements.

Strain response was measured on the top and the bottom layer of the specimen during HPU irradiation. Three strain gages were mounted on the top surface centered at 1.375 inch, 2.375 inch, and 3.875 inch from the longitudinal center of the specimen and the other three were mounted in corresponding locations on the bottom. The HPU impacted on the top layer at the longitudinal center and the specimen was clamped at 1 inch from both ends. The strain amplitude versus frequency analysis of the response of each gage was obtained and used to compute the corresponding experimental stresses at the location of the gage. The experimental data of stresses were then used to calibrate the magnitude of analytical stresses at the corresponding location computed from NASTRAN. Once the analytical stresses at the surface layer were calibrated, a conversion ratio was found and then used to calibrate the analytical stresses at the bondline.

Results of strain response measurements for the 1D Al-Adhesive-Al specimen are shown in Figures 13 and 14. In Figure 13, A-1, A-2, and A-3 are strain vs. frequency plots for the gages mounted on the top surface centered at 1.375 inch, 2.375 inch and 3.875 inch, respectively, from the center of the specimen. The plots A-4, A-5, and A-6, shown in Figure 14, are those for the other 3 gages mounted in the corresponding locations on the bottom surface of the specimen. In all cases, in addition to the presence of the 20 KHz input frequency, there are several low frequency modes with comparable amplitudes being excited.

An attempt of frequency matching between the computed and experimental data was not successful. It is possible that in the finite-element analysis more than 20 elements are needed to obtain more accurate normal mode frequencies particularly in the high frequency region. Obviously, improvement in resolution of strain gage measurements will be needed to resolve the discrepancy. Although a rigorous frequency matching is not possible, we have chosen three vertical bending modes that are

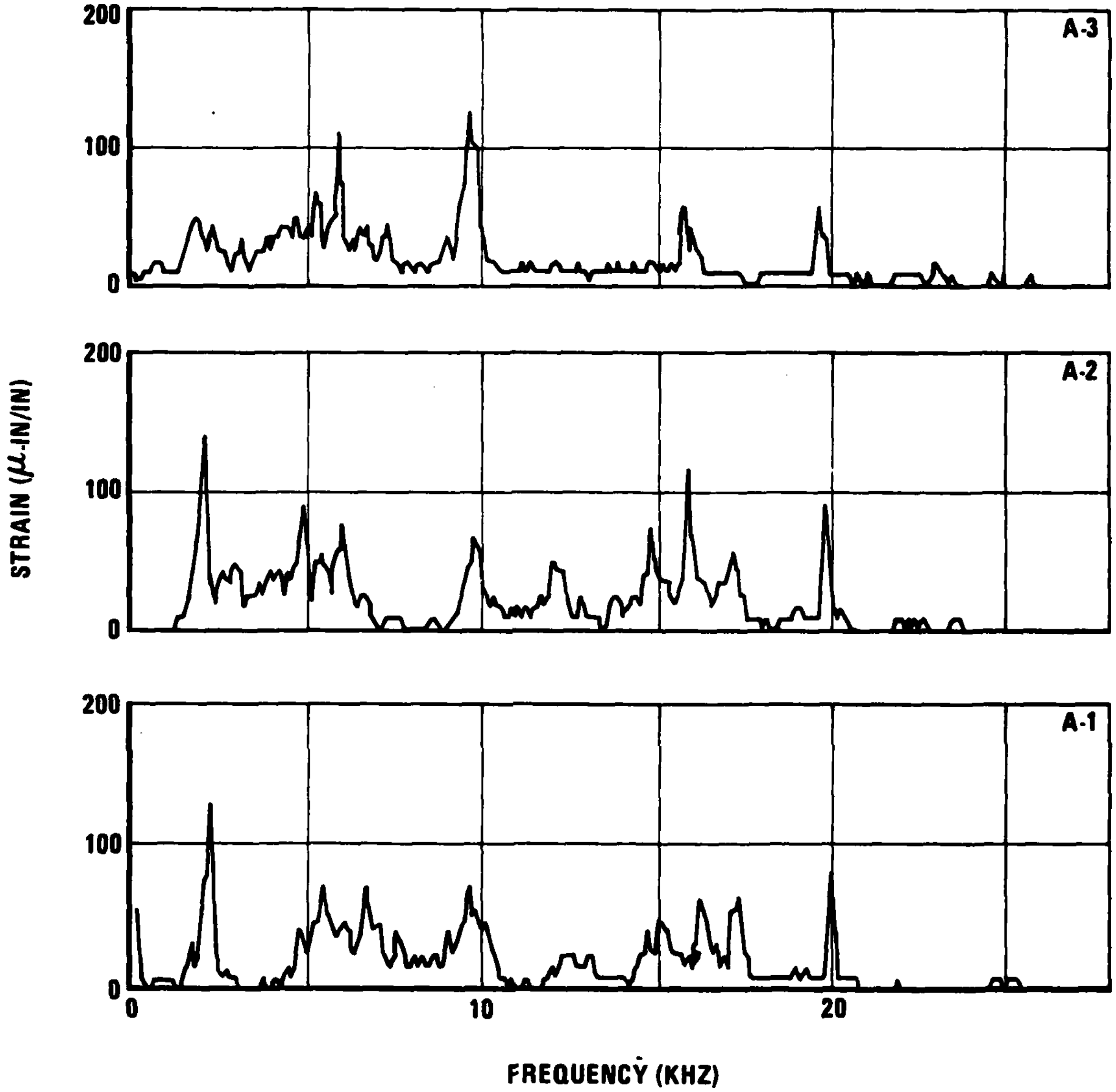


FIGURE 13 STRAIN VS FREQUENCY PLOTS FOR 1D AL/AL SPECIMEN(1)

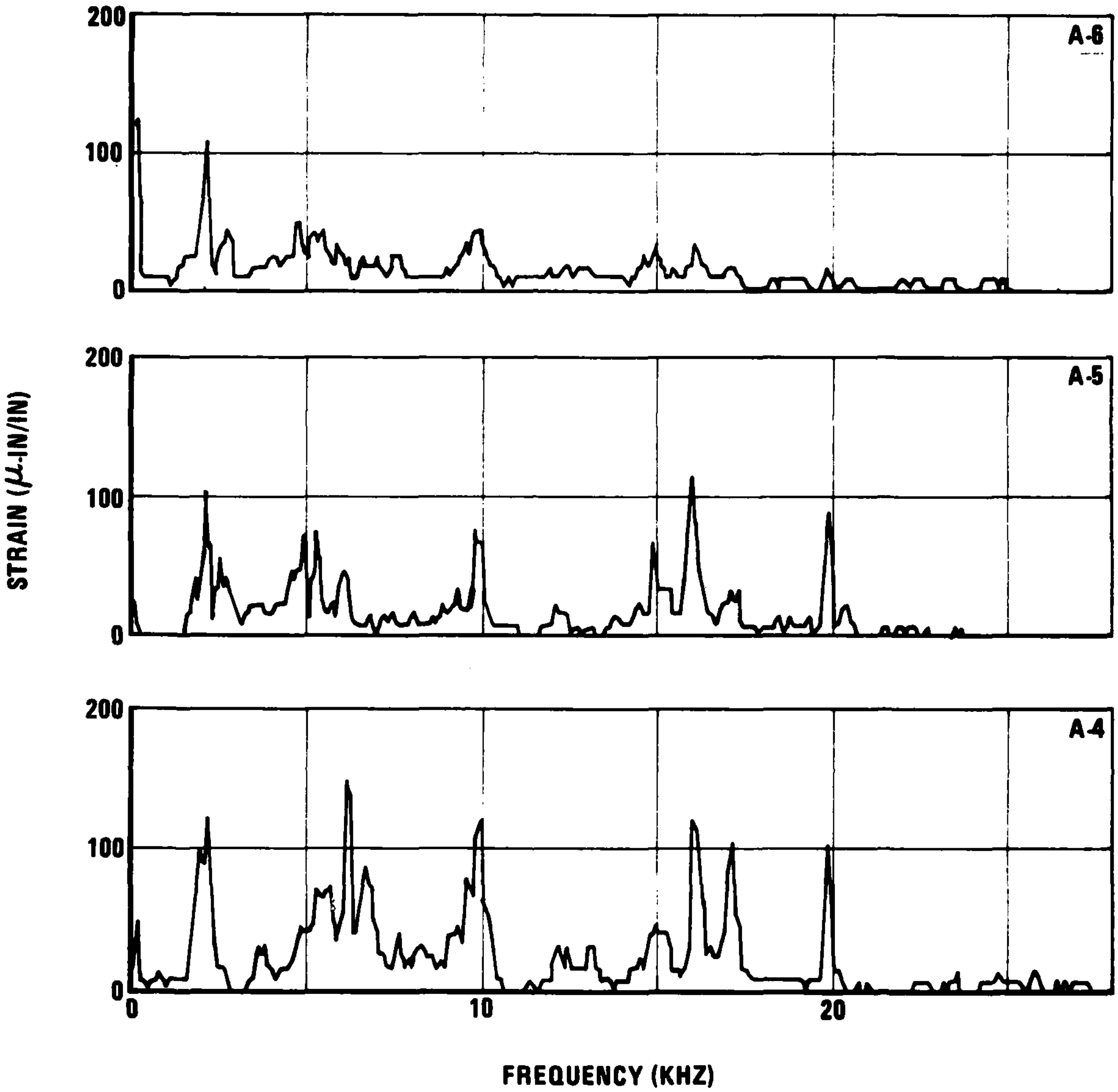


FIGURE 14 STRAIN VS FREQUENCY PLOTS FOR 1D AL/AL SPECIMEN (2)

reasonably close in frequency to dominant peaks of the strain gage data to analyze the corresponding shear stresses at the bondline. Estimation of experimental to analytical stress ratios was done by converting strain to stress at each gage location and then comparing it with analytical stresses at the surface grid points corresponding to the gage locations. One would expect the stress ratios at the three gage locations to be equal for a given mode. The fact that they are not, simply emphasizes the crudeness of the analysis. However, in two of the vertical bending modes the ratios are close enough to warrant further consideration for predicting shear stresses at the bondline. Estimated analytical shear stresses at the bondline for these two modes are shown in Table 11. Since the first two elements at the boundary give less accurate values, the shear stress calculated for these two elements is discarded. The maximum bondline shear stresses for the two modes, 6887 Hz and 15668 Hz, are about 2000 - 1700 psi. The values are not much different from the one calculated in the previous analytical model. Although the present analytical approach may be plausible, some improvements in both computer modeling and strain response measurements are needed to increase the confidence level on the predicted shear stresses at the bondline.

Strain response was also measured for a 1D (1x10x0.25 inch) GrE/GrE bonded specimen and also a 2D (10x10x0.25 inch) Al/Al bonded specimen for comparison. As in the 1D Al/Al specimen, some low frequency modes were excited in the 1D GrE/GrE specimen as shown in Figures 15 and 16. Strain gage arrangement was similar to that in 1D Al/Al specimen. Gage locations of B-1 to B-6, in Figures 15 and 16, correspond to those of A-1 to A-6 in Figures 13 and 14. Figure 17 shows strain vs. frequency plots for a 2D Al/Al specimen. The HPU irradiated at the center of the plate and the gages C-1 and C-2 were mounted on the top surface, 1 inch and 4 inches from the center, respectively. There was only one frequency, 20 KHz, observed from both gages. The strain amplitude at C-1 was 160 μ-inch/inch while it was 110 μ-inch/inch at C-2. This result indicated that no natural frequency of the plate was excited by HPU and that the amplitude of the ultrasonic stress wave propagating laterally through the plate was attenuated considerably.

From the above preliminary study, the effect of HPU on the 2D plate specimen is a localized effect while it is a resonance effect in 1D specimens. Applications of analytical models developed for 1D specimens to the plate specimens may not be feasible. Since 2D plates resemble the real-life structures better than the 1D specimen, analytical efforts should be emphasized on the 2D-plate and they are probably more pratical since the HPU effect is localized.

TEMPERATURE EFFECTS.

When an adhesively bonded structure is heated at a temperature near or exceeding the adhesive cure temperature, the adhesive

TABLE 11 ANALYTICAL SHEAR STRESS PREDICTED AT THE BONDLINE

Element	Londitudinal Position (Distance from the center of the specimen in In.)	Shear Stress at the Bondline (PSI)	
		Normal mode freq. 6887 Hz	Normal mode freq. 15678 Hz
201	3.8	1041	485
202	3.6	-5400	3427
203	3.4	-2756	1645
204	3.2	-3089	1073
205	3.0	-2099	-205
206	2.8	-1293	-1182
207	2.6	-286	-1828
208	2.4	678	1904
209	2.2	1535	-1418
210	2.0	2778	-511
211	1.8	2538	544
212	1.6	2575	1468
213	1.4	2288	1970
214	1.2	1715	1922
215	1.0	927	1348
216	0.8	2373	428
217	0.6	-888	-537
218	0.4	-1686	-1245
219	0.2	-2293	-1345
220	0	-2601	-873

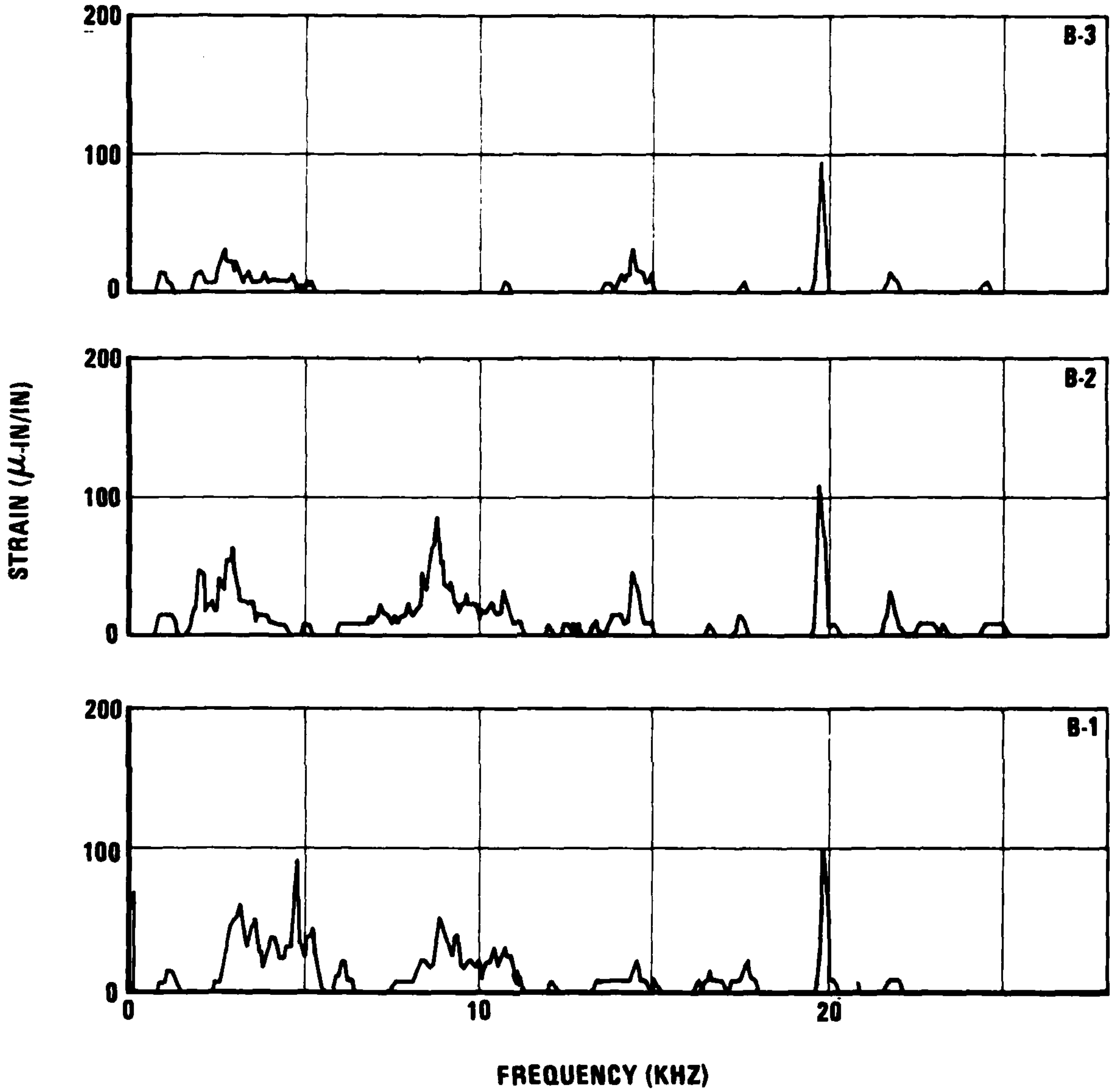


FIGURE 15 STRAIN VS FREQUENCY PLOTS FOR 1D COMP/COMP SPECIMEN (1)

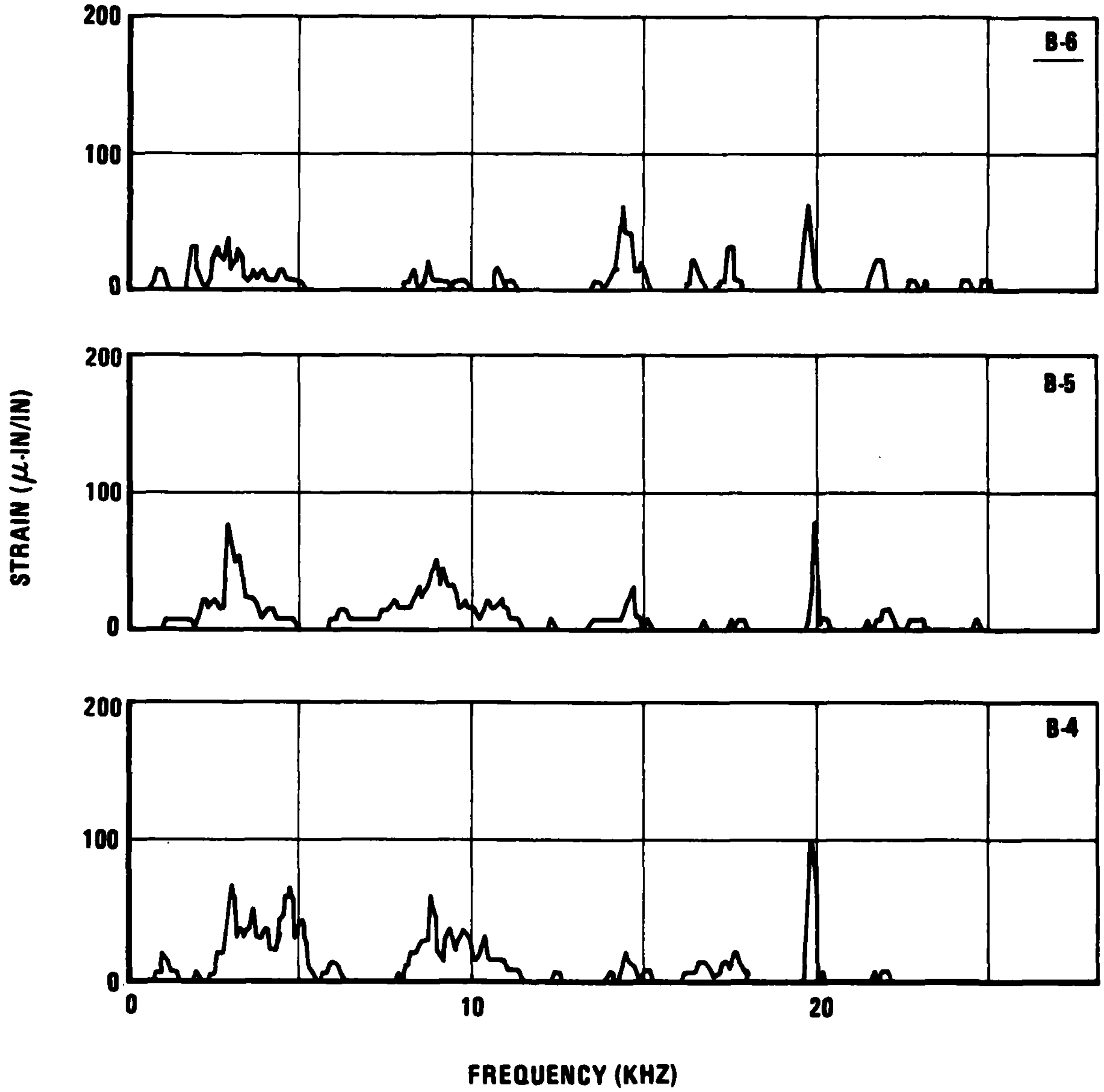


FIGURE 16 STRAIN VS FREQUENCY PLOTS FOR 1D COMP/COMP SPECIMEN (2)

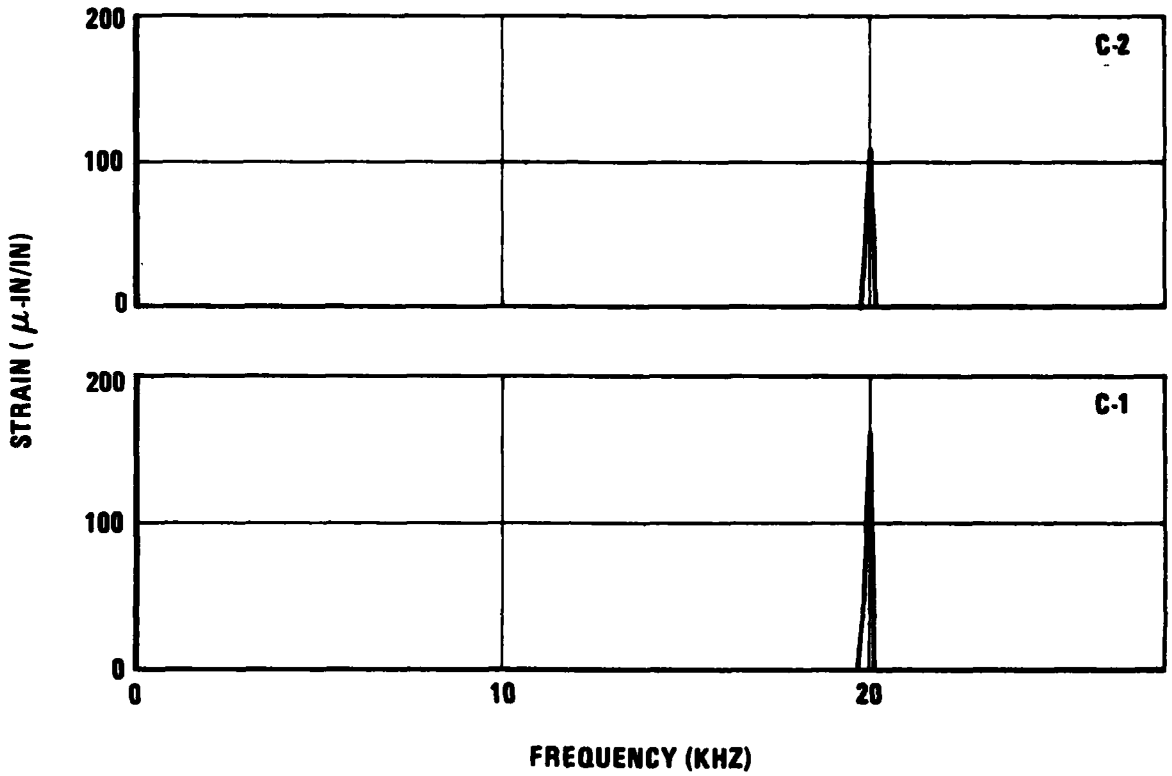


FIGURE 17 STRAIN VS FREQUENCY PLOTS FOR 2D AL/AL SPECIMEN

bond will be weakened. If the temperature increase in a good bond, a specimen during HPU irradiation is substantially high, cumulative damage of the adhesive bond will be inevitable although no immediate debond is observed. Therefore, it is important to check the actual temperature increase in the good bond specimen as well as in the weak bond specimen during HPU irradiation.

An Inframetric infrared thermal imaging system was used to measure the temperature at the bondline of specimens during HPU irradiation. The system was set to perform a line-scan of the temperature profile along the bondline of the specimen. The temperature profile was displayed on the monitor screen and a Polaroid™ camera was used to obtain a record of the profile.

Two GrE/GrE specimens bonded with EA9649R adhesive were tested. One specimen was cured at normal cure temperature (350°F) and another was cured at a lower temperature (150°F) to produce a weak bond condition. The dimensions of the specimen were 1x10x0.25 inch. The specimen was irradiated by HPU at the center of the flat surface and the specimen was clamped at both ends. The infrared thermal imaging system was set to monitor temperature across the bond line of the specimen. Temperature was recorded immediately at the end of each irradiation time. Examples of the measured temperature profile are shown in Figure 18. Pictures (A) and (B) show the temperature profile for the under-cured and cured specimen, respectively, after 1.0 second of HPU irradiation. The abscissa represents the length of the specimen and the ordinate represents the temperature. Each horizontal line represents 10°F increment of temperature. The base line is 80°F. Plots of bondline temperature versus HPU irradiation time for the under-cured and the cured specimens are shown in Figure 19(A) and (B), respectively. For the under-cured specimen, the temperature increased drastically with increasing HPU irradiation time. After 1.5 seconds of irradiation, the temperature increased to 215°F. For the cured specimen, the temperature did not increase significantly during HPU irradiation. It only increased to 115°F after 3.0 seconds of irradiation.

The temperature increase due to HPU irradiation can be understood as the result of energy absorption at the bondline. The present test result showed that the under-cured adhesive absorbed more energy from the stress waves than the cured adhesive.

Al/Al bonded specimens were also tested. Due to the high-thermal conductivity of aluminum plates, the recorded temperature did not represent the actual temperature increase at the bondline during HPU irradiation. However, the highest temperature recorded for this type of specimen was 105°F at 1.3 seconds of HPU irradiation.

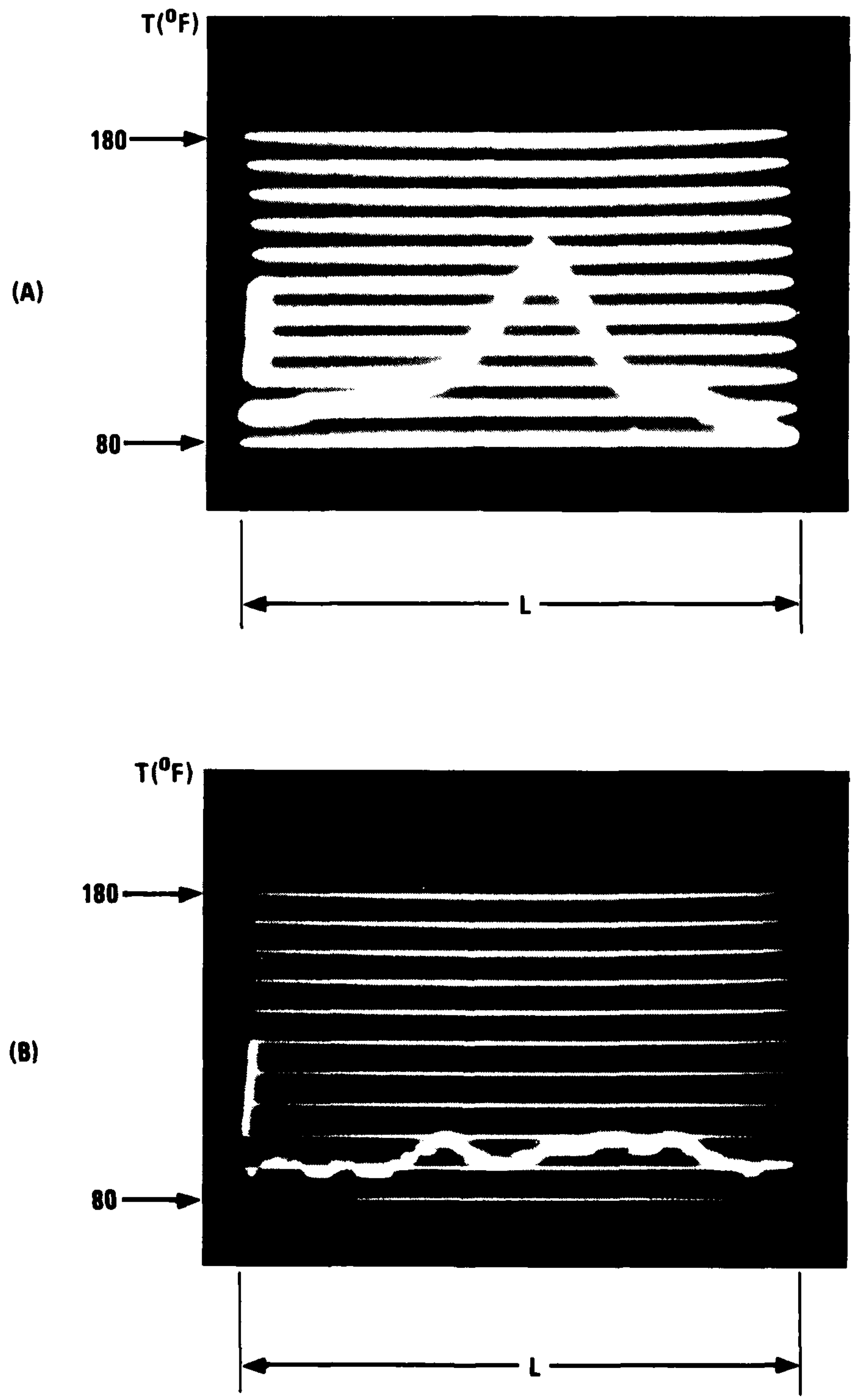


FIGURE 18 TEMPERATURE PROFILE AT BONDLINE AFTER 1.0 SEC OF IRRADIATION: (A) UNDER-CURED; (B) CURED COMPOSITE SPECIMEN

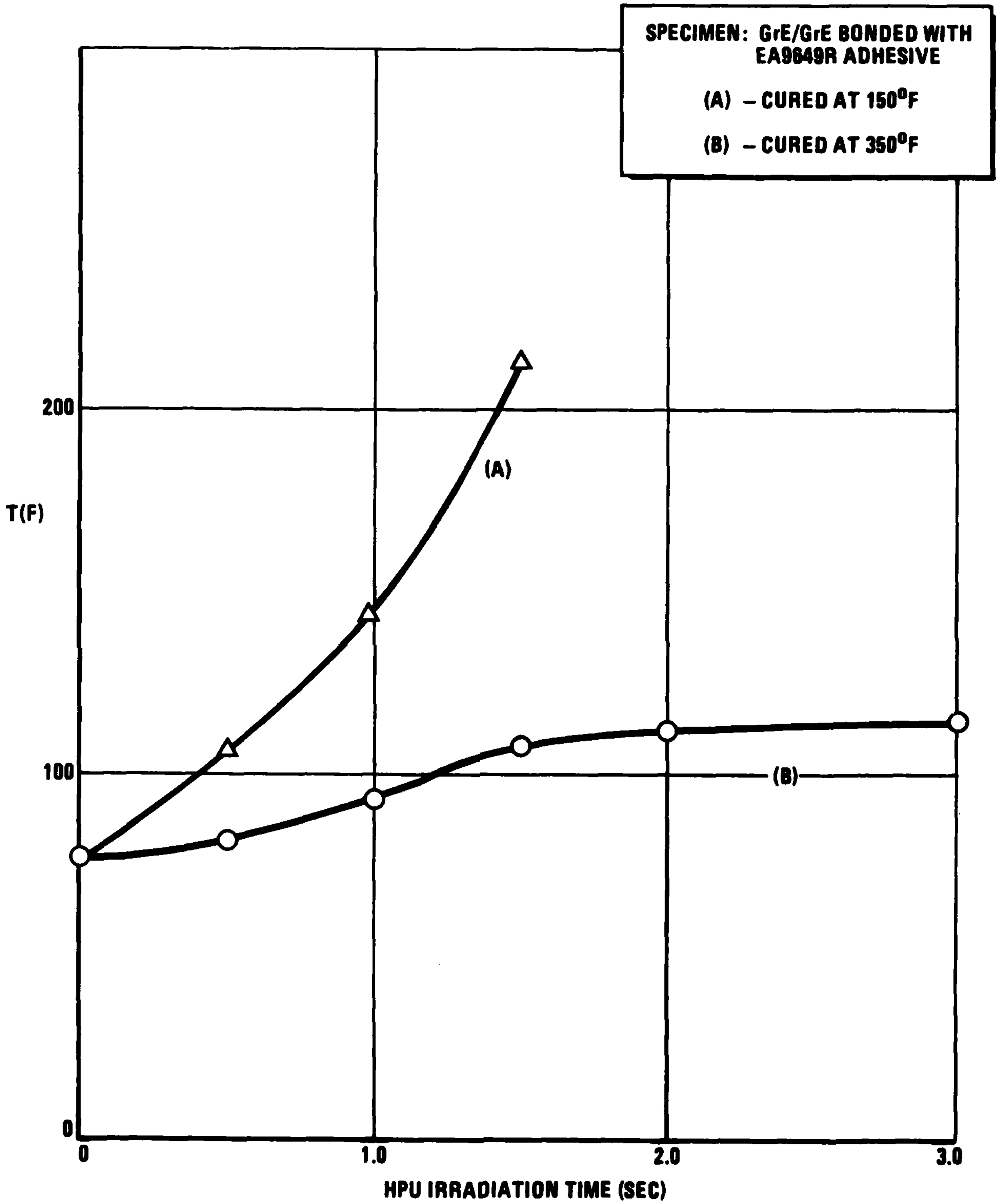


FIGURE 19 BONDLINE TEMPERATURE DURING HPU IRRADIATION

CONCLUSIONS

At the completion of this 18-month contract, the following conclusions are made:

(1) A bond strength screening system using high power ultrasound has been designed and made portable for either laboratory or field inspection.

(2) The system can detect weak bonds in bonded structures produced by contamination of bonding surfaces or by insufficient cure of adhesive. The bond strength of weak bonds defined above is about 50% or less than that of good bond specimens prepared using standard bonding procedures.

(3) Power levels of high power ultrasound required to disrupt weak bonds without damaging good bonds in three types of bonded structures, Al/Al, GrE/GrE, and GrE/Honeycomb core structures, have been determined experimentally.

(4) Analytical studies of high power ultrasound effects on a narrow strip specimen have been attemped. Excitation of low frequency vibration modes in the specimen, observed from strain response measurements, complicated the analytical modeling of high power ultrasound debonding process in the simple one-dimension specimen.

(5) No low frequency modes other than the 20 KHz input frequency have been observed in a plate (two-dimensional) specimen. This phenomenon indicates that the effect of high power ultrasound in a large plate structure may be localized.

(6) Temperature increase at the bondline during high power ultrasound irradiation has been found to be the major factor for debonding of insufficiently cured adhesive. For standard cured specimens, no significant temperature increase has been observed and hence the possibility of thermal degradation of normal cured adhesive by high power ultrasound is negligible.

In summary, the HPU system developed under this 18-month contract has shown its capability in screening weak bonds in three types of bonded structures, Al/Al, GrE/GrE, and GrE/Honeycomb core structures. System evaluation has shown that the system is suitable for NDI inspection in the production line for screening defective Al/Al parts and repaired honeycomb core structures. However, quantitative correlations between the input HPU power level and the bond strength of the test specimens have been roughly established only in one group of Al/Al specimens. In order for the system to have a wide range of applications, quantitative correlations mentioned above should be obtained for various types of aircraft structures, particularly the composite/

metal bonded structures.

Since it is difficult and also expensive to establish such quantitative correlations for various types of bonded structures experimentally, more analytical work in this area should be emphasized. A successful analytical model should be able to correlate the input HPU energy with the following parameters: the adhesive bond strength, types of adhesive and adherends, and the dimension of the test structure. To acheive this goal, some good experimental data should be obtained for comparison with the predicted analytical data and used as a guideline for improving the analytical model.

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